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Interagency Energy/Environment R&D Program Report

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I. INTRODUCTION

The purpose of this report is to present current technology for measurement of the following parameters:

- Flowrate of coal as a dry solid
- Flowrate of coal in a coal/water slurry
- Coal composition

Implicit in some techniques for slurry flow measurement is a supplementary measurement of slurry density. Composition measurements may apply to a single constituent, such as sulfur, or to a more complete elemental analysis. The reason for this technology assessment is to keep the Environmental Protection Agency abreast of instrumentation developments in the above areas. There are many potential applications for environmental quality improvement, especially in the areas of process control. At the source of coal combustion, continuous real time or quasi-real time (instrument response times of 1-5 minutes) coal flow rate and composition data could be used effectively to optimize both the combustion process itself and the performance of pollution control devices. This same knowledge would also be useful at coal cleaning facilities, and directly in the mine for such activities as preliminary sorting of high and low sulfur coals. The possible growth in the near future of long distance coal conveyance via slurry pipelines also creates an interest in slurry instrumentation.

The basic finding during the investigation has been that adequate standard instrumentation is available for the flow measurements, but continuous analysis equipment is still largely in the development stage, with the first production unit scheduled for delivery at the end of 1979. The presently preferred technique for dry coal flow measurement is the weigh belt, using either a mechanical or electronic load sensor. Due to their simplicity, nuclear weight scales using a gamma ray technique are also becoming popular for conveyor belt measurements. Magnetic flowmeters are most common for slurry flow measurement, and are acceptable when properly used. They must be used in conjunction with a density meter to determine the percentage of coal in the slurry. Several new ultrasonic flowmeters also appear capable of good accuracy in dense slurry flow measurement. Fast neutron activation techniques are the most promising for coal analysis instrumentation, but, as mentioned above, are still largely in the development stage.

The report gives the technical background (physics of operation) of the methods considered applicable. This is followed by discussion of the development status of each of the techniques. Since not all techniques have reached the production stage, estimates of instrument development and availability over the next ten years are given, along with potential instrument uses. This last section, as originally written in early 1978, was updated in mid-1979, primarily to note progress by SAI on nuclear coal analysis instrumentation. As an appendix, procedures for weigh belt calibration and use formulated by the Southern Weighing and Inspection Bureau are presented.

There has long been a strong need for flow measurement instruments in the coal industry for accounting/sales purposes, and this resulted in the development of high accuracy weigh belt techniques. Magnetic flowmeter development arose from a more general need for a non-intrusive flow measurement technique. System accuracy for the slurry flow measurement is not, and probably never will be, as good as that for conveyor belt measurements. Finally, instrumentation for continuous coal analysis is needed to satisfy more recent demands for improved environmental quality and efficient energy usage, and lags in development compared to the flow instruments, primarily because the analysis measurements are inherently more difficult to make. The combined flow and analysis measurements will be able to be used to determine elemental mass flow rates, which are required for optimum process control.

II. PRINCIPLES OF INSTRUMENT OPERATION

This report is focused on flow and composition measurements of coal streams, either dry or entrained in water. For the types of instruments under consideration, flowrates are measured as volumetric flow or mass flow, and composition measurements are performed in terms of mass fractions. Flowrate data is primarily of interest for process control and also directly for pollution monitoring (e.g., sulfur content). The combination of flowrate and composition can yield constituent mass flow rates (e.g., carbon, ash, sulfur) which may be of greater use for accurate process control than either the total flow or the composition measurements. A brief mathematical base, from a system viewpoint, is presented below to provide a context for the variety of measurement concepts which follow. The following single equations describe the measurements analyzed in detail in this report:

1. Dry Solid Mass Flow:

$$\dot{m}_T = \frac{m}{\ell}\dot{\ell} \qquad (1)$$

where

$\dot{m}_T$ = total mass flowrate, kg/s
m = mass present in sensing section at time of measurement, kg
ℓ = length of sensing section, m
$\dot{\ell}$ = speed of conveyor belt, m/s

2. Slurry Mass Flow

$$\dot{m}_T = \rho_{sl}\,\bar{u}\,A \qquad (2)$$

where

$\bar{u}$ = average slurry velocity, m/s
ρ_{sl} = local slurry density, kg/m^3
A = local pipe cross-sectional area, m^2

3. Constituent Mass Fraction

$$X_i = \frac{m_{i_e}}{V_e \rho_m} \qquad (3)$$

where

X_i = mass fraction of constituent i, dimensionless
m_{i_e} = sensed mass of constituent i within the effective sampling volume during the total sampling time, kg
V_e = effective sampling volume (must be established by in-place calibration), m^3
ρ_m = density of material in sampling volume, kg/m^3

4. Constituent Mass Flow

$$\dot{m}_i = \dot{m}_T X_i \tag{4}$$

where

$\dot{m}_i$ = mass flow rate of constituent i, kg/s

5. Slurry Density

$$\rho_{sl} = \frac{V_s}{V_T}\rho_s + \frac{V_\ell}{V_T}\rho_\ell \tag{5}$$

where

V_T = locally defined control volume, m^3
V_s = volume of solids in control volume, m^3
ρ_s = average density of solids in control volume, kg/m^3
V_ℓ = volume of liquid in control volume, m^3
ρ_ℓ = average density of liquid in control volume, kg/m^3

These equations are set up to reflect the way in which the measurements are actually performed. Equation (4) shows the simple but key point that both mass flow and composition measurements are required to obtain constituent mass flow rates. Equation (5) is used by itself, with ρ_{sl} as the actual measured parameter, to determine percent solid and percent liquid in slurry streams, and then in conjunction with equation (2) to determine solid and liquid mass flow rates.

The detailed presentations in the remainder of this section deal with the physics of the instruments used to measure the parameters in Equations (1)-(5). Since the coal analysis techniques are not yet fully developed, more detail is presented for them in order to give an idea of their ultimate capabilities and limitations.

2.1 COAL ANALYSIS INSTRUMENTS (Ref. 1-3)

Any analysis of instrumentation designed to measure coal must take account of its extremely inhomogeneous nature with regard to composition and physical form. For this reason before embarking upon a discussion of the instrumental technologies, the range in magnitude of applicable quantities and their definitions are summarized in this introductory section.

In most cases the definitions employed will be those of the ASTM. The terms of greatest interest are defined as follows in ASTM Designation D121-72:

Standard Definitions of Terms Relating to Coal and Coke - As Specified in ASTM Designation D121-72

" proximate analysis — in the case of coal and coke, the determination, by prescribed methods, of moisture, volatile matter, fixed carbon (by difference), and ash.

ultimate analysis — in the case of coal and coke, the determination of carbon and hydrogen in the material, as found in the gaseous products of its complete combustion, the determination of sulfur, nitrogen, and ash in the material as a whole, and the estimation of oxygen by difference.

NOTE 1 — The determination of phosphorus is not by definition a part of the ultimate analysis of coal or coke, but may be specified when desired.

NOTE 2 — When the analysis is made on an undried sample, part of the hydrogen and oxygen as determined is present in the free moisture accompanying the coal. Therefore, in comparing coals on the basis of their ultimate analysis, it is advisable always to state the analysis on both the "as-received" and "dry" bases.

NOTE 3 — Inasmuch as some coals contain mineral carbonates, and practically all contain clay or shale containing combined water, a part of the carbon, hydrogen, and oxygen found in the products of combustion may arise from these mineral compounds.

moisture — essentially water, quantitatively determined by definite prescribed methods which may vary according to the nature of the material.

NOTE 1 — Such methods may not determine all of the water present.

NOTE 2 — In the case of coal and coke the methods employed shall be those prescribed in ASTM Methods D 271, Laboratory Sampling and Analysis of Coal and Coke.

equilibrium moisture of coal — the moisture content retained at equilibrium in an atmosphere over a saturated solution of potassium sulfate at 30 C, and 96 to 97 percent relative humidity. When the sample, before such equilibration, contains total moisture at or above the equilibrium moisture may be considered as equivalent to inherent or bed moisture; and any excess may be considered as extraneous moisture.

ash — inorganic residue remaining after ignition of combustible substances, determined by definite prescribed methods.

NOTE 1 — Ash may not be identical, in composition or quantity, with the inorganic substances present in the material before ignition.

NOTE 2 — In the case of coal and coke, the methods employed shall be those prescribed in Methods D 271.

volatile matter — those products exclusive of moisture, given off by a material as gas or vapor, determined by definite prescribed methods which may vary according to the nature of the material.

NOTE — In the case of coal and coke, the methods employed shall be those prescribed in Methods D 271.

fixed carbon — in the case of coal, coke, and bituminous materials, the solid residue other than ash, obtained by destructive distillation, determined by definite prescribed methods. "

The ASTM utilizes these definitions plus calorific value to classify coals by rank. Table 1 summarizes the system. The substantial variations in composition associated with the various ranks are typified by the example in Table 2. The reported ranges are by no means all-inclusive but only representative of a typical bed within the listed state. Of particular importance are the wide variations in moisture, ash and sulfur content.

Moisture content is extremely variable because it depends both upon the mine and upon the coal treatment after mining. For example, air drying can reduce the moisture content. On the other hand exposure to rain or snow can raise it. The situation is further complicated by the

Table 1. ASTM DESIGNATION D 388 CLASSIFICATION OF COALS BY RANK

Class	Group	Fixed Carbon Limits, percent (Dry, Mineral-Matter-Free Basis)		Volatile Matter Limits, percent (Dry, Mineral-Matter-Free Basis)		Calorific Value Limits Btu per pound (Moist. Mineral Matter-Free Basis)	
		Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Equal or Greater Than	Less Than
I. Anthracite	1. Meta-anthracite	98			2		
	2. Anthracite	92	98	2	8		
	3. Semianthracite	86	92	8	14		
II. Bimuninous	1. Low volatile bituminous coal	78	86	14	22		
	2. Medium volatile bituminous coal	69	78	22	31		
	3. High volatile A bituminous coal		69	31		14,000	
	4. High volatile B bituminous coal					13,000	14,000
	5. High volatile C bituminous coal					{ 11,500 { 10,500	13,000 11,500
III. Subbituminous	1. Subbituminous A coal					10,500	11,500
	2. Subbituminous B coal					9,500	10,500
	3. Subbituminous C coal					8,300	9,500
IV. Lignitic	1. Lignite					6,300	8,300
	2. Lignite						6,300

Table 2. TYPICAL ANALYSIS OF COAL OF THE UNITED STATES

State	County	Rank	Proximate analysis, percent by weight				
			Moisture	Volatile Matter	Fixed Carbon	Ash	Sulfur
Pennsylvania	Lackawanna	Anthracite	4.3	5.6	80.6	9.5	0.6
	Usual range		Dry coal	4-7	80-86	9-14	0.5-0.9
Arkansas	Johnson	Semianthracite	2.5	12	76.1	9.4	2.3
	Usual range		1-3	11-14	75-82	6-12	1.3-3.8
West Virginia	McDowell	Low-volatile bituminous	2.7	17.6	73.7	6	0.7
	Usual range		1-5	15-22	72-74	4-9	0.5-0.9
Pennsylvania	Clearfield	Medium-volatile bituminous	2.7	21.6	66.9	8.8	1.8
	Usual range		1-4	21-26	64-70	7-13	1-3.3
Kentucky	Harlan	High-volatile A	3	36.9	56.6	3.5	0.7
	Usual range		2-4	37-40	57-60	3-6	0.5-1.2
Ohio	Perry	High-volatile B	7.8	36	47.3	8.9	2.0
	Usual range		7-10	37-42	49-53	7-11	1-3.5
Illinois	Christian	High-volatile C	13.5	35.6	39.3	11.6	4.2
	Usual range		12-14	40-42	44-47	12-15	4.4-5.5
Wyoming	Carbon	High-volatile C or subbituminous A-subbituminous B	12.8	37.1	43.5	6.6	0.5
	Usual range		9-17	39-45	47-56	4-10	0.3-1.3
Utah	Morgan	Subbituminous B	17.9	27.7	36.7	17.7	0.5
Washington	Stevens	Subbituminous C	16.4	29.8	34.8	19	2.0
North Dakota	Billings	Lignitic	38.0	25.8	29.4	6.8	0.6

fact that moisture may deliberately be added to the coal either to prevent spontaneous combustion or as a by-product of coal cleaning operations. Such additions are not uniformly distributed throughout the coal but tend to be more concentrated near the surface.

The variations in coal ash are due to similar complexities. The ash arises from several sources. Because coal is extremely inhomogeneous there are bulk contaminants distributed throughout the coal even within the seam. Furthermore, inevitably contaminants such as clay, shale and other rocks from the floor and roof of the seam are included along with the coal. These types of contaminants are the ones typically removed by coal cleaning methods. In addition, inorganic materials which are inherently chemically contained in the coal contribute to the ash content. Typical ranges for the ash content associated with the sum of both of these contributions are shown in Table 3.

Table 3. TYPICAL ASH CONTENTS

SiO_2	20-60
Al_2O_3	10-35
Fe_2O_3	5-35
CaO	1-20
MgO	0.3-4
TiO_2	0.5-2.5
$Na_2O + KO_2$	1-4
SO_3	0.1-12

It is apparent from the above discussion that there are substantial variations in the composition of coal obtained from different sites. A far more critical problem from a measurement standpoint is that large variations occur within even relatively small volumes of coal. For this reason extremely detailed sampling procedures have been developed and are documented by organizations such as ASTM. The basic objective of these techniques is to obtain a small representative sample from a large volume of material. Typically this is achieved by taking a large number of moderate size samples. These samples are then ground to a reduced size and thoroughly mixed. New samples are obtained from the resultant mixture and the process iterated until a suitably uniform mixture is obtained. Details of sampling equipment, procedures and accuracy can be obtained in volume 26 of the ASTM Standards and will not be repeated here. From a process control standpoint the most significant feature of these procedures is that they are quite time consuming. In practice typically hours are required and even under the most optimistic of conditions it is hard to imagine sampling times less than several minutes. Some of the nuclear measurement techniques are particularly attractive for process control because they probe large sample values and do not require such sampling approaches.

2.1.1 Background Information on Nuclear Interaction (Ref. 4-6)

In order to develop a basis for understanding the nuclear diagnostic technologies a brief introduction to the pertinent interactions is presented in the following sections. First, the concept of a cross-section is reviewed and the distinction between attenuation and absorption is made. Next, photon-matter interactions are discussed. Finally, neutron-matter interactions are considered.

2.1.1.1 The Cross Section Concept

The concept most often utilized to quantify the probability of nuclear reactions is the cross-section and is typically denoted by the symbol σ with an appropriate subscript. A cross section can be visualized as an area presented by scatterers to an incident beam and is obtained from the ratio

$$\frac{\text{\# incident particles scattered per second}}{\text{\# incident particles per unit area per second}}$$

Consider for example, a slab containing scatterers which can be thought of as hard spheres of radius R which absorb an incident particle if it strikes them. The geometrical cross section of each sphere is obtained from the expression

$$A = \pi R^2 \text{ cm}^2/\text{sphere}$$

Assume that the slab has an area A, a thickness t and contains N scatterers per unit volume. The number of scatterers per unit area is therefore:

$$\frac{N \frac{\text{scatterers}}{\text{cm}^3} A(\text{cm}^2)\ t(\text{cm})}{A\ \text{cm}^2} = Nt\ \frac{\text{scatterers}}{\text{cm}^2}$$

If the slab is thin enough that the scatterers do not shadow each other (i.e., $Nt\sigma << 1$), then the probability of an incident point particle striking a scatterer is

$$P = (Nt)\ \sigma \tag{6}$$

Usually single scattering events are not investigated but rather a number of particles are incident on the scattering material. For instance, if n incident particles per cm^3 moving with a velocity V are incident on the target, the flux $S = nV$ particles/cm^2 and the anticipated number of scattering events per cm^2 of target is equal to the expression

$$(nV) \cdot (Nt\sigma) \tag{7}$$

from this viewpoint an alternative expression for the cross section is

$$\sigma = \frac{\text{collisions per square centimeter per second}}{\text{(particle flux) (scatterers/square centimeter)}}$$

In practice this expression is the one which is most frequently utilized.

The above simple case can also be used to derive the well-known exponential attenuation behavior. Consider the penetration of an incident flux S(o) to a depth X into the slab. Evidently from equation (7):

$$dS(X) = -S(X)\ (N\sigma\ dX)$$

$$\frac{dS}{dX} = -SN\sigma$$

the obvious solution is the function

$$S(X) = S(o)\ e^{-N\sigma X} \tag{8}$$

The quantity $N\sigma$ is referred to as a linear attenuation coefficient per cm of travel and is frequently utilized instead of the cross section to characterize a target material.

The cross section concept is much more general than the above discussion indicates. It should be appreciated that the effective area concept is just a visualization aid and that in fact nothing in the system actually need have this particular geometrical area. Furthermore, although the interaction of a particular incident particle is indeed either an all or nothing process, the event need not be an absorption. In a more general sense any type of interaction process can be said to possess a cross section. A complete specification of a scattering event requires a delineation of the incident particles, the target, and the products after scattering. These products can include particles not even present before the interaction. The complete specification also requires a detailed knowledge of the quantum states of all involved particles.

As an illustration of the subtleties involved, consider the concepts of attenuation, scattering and absorption of photons. The linear attenuation coefficient μ is equal to the total cross section per scatterer (i.e., the sum of all processes) multiplied by the number of scatterers per cm^3. It includes both elastic processes in which the photon is merely deflected without giving up energy and processes in which the photon energy is actually absorbed by the scattering medium. The elastic processes are referred to as elastic scattering and are characterized by a scattering coefficient μ_s. The absorption processes are characterized by an absorption coefficient μ_a. The attenuation coefficient incorporates both processes:

$$\mu = \mu_s + \mu_a \tag{9}$$

It should be appreciated that if desired, both μ_s and μ_a can be further broken down into various subclasses.

2.1.1.2 Interaction of Gamma Radiation With Matter

Gamma rays are photons which accompany nuclear transitions. The gamma-ray matter interaction is characterized by the fact that each γ-ray is removed in an all-or-nothing manner from the incident beam. Several competing alternative reactions can occur. The principle possibilities are an interaction with the entire atom, an interaction with a single electron, or with the atomic nucleons.

In each type of interaction the number of photons removed is proportional to the thickness traversed and is evidently a solution of the differential equation

$$\frac{dI}{dX} = -\mu I \qquad (10)$$

where

I = incident intensity
μ = linear attenuation coefficient
X = depth into scatterer

For the simple homogeneous monoenergetic case the solution to the equation is the well known exponential attenuation $I = I_0 e^{-\mu X}$. This simple viewpoint expresses the basic concept embodied in the study of nuclear interactions. The study of γ interactions focusses upon the determination of μ as a function of γ ray energy and material and upon the products of the incident gamma rays that are interacted with.

In applications relevant to the diagnostic utilization of gamma rays several types of process are significant and dictate the selection of suitable gamma rays. At low energies the predominant interaction process is the photoelectric effect. The precise energy at which this statement is correct is highly dependent upon the atomic number (Z) of the scattering atom but roughly speaking these effects dominate at energies of order 1 Kev–500 Kev. In the photoelectric effect the incident photon is absorbed by a bound electron and one electron is emitted usually from the K or L shell. Energy conservation yields

$$h\nu_i = Be + KE \qquad (11)$$

where

$n\nu_i$ = incident gamma ray energy
Be = binding energy of electron prior to ejection
KE = electron kinetic energy

The excited atom promptly emits a characteristic X-ray or an Auger electron as it relaxes to a lower level. This type of process is quite sensitive to the energy of the gamma ray and to the specific atomic scatterer involved and is the basis of X-ray fluorescence studies as discussed further below.

As the gamma ray energy increases to become much larger than the binding energies eventually the precise bound-state of the electron becomes of minor importance and the probability of interacting with single electrons becomes the dominant interaction. The scattering is as if the electrons were free and at rest. This is known as the Compton Effect and dominates at energies of ∿ 0.5-1.5 Mev. The situation is illustrated in Figure 1 and energy and momentum conservation yield the equations

$$\frac{1}{h\nu'} - \frac{1}{h\nu_o} = \frac{1}{m_o c^2}(1 - \cos\phi) \qquad (12)$$

$$\lambda' - \lambda_o = \frac{h}{m_o c}(1 - \cos\phi). \qquad (13)$$

The important points to note are that the Compton shift in wavelength in any particular direction is independent of the incident photon energy but that the energy shift increases strongly as $h\nu_o$ increases. Solving for ν' yields:

$$\nu' = \frac{\nu_o}{1 + \alpha(1 - \cos\phi)} \qquad (14)$$

where $\alpha = \frac{h\nu_o}{m_o c^2}$

It is apparent that if this type of scattering is averaged over all angles, a continuous distribution of energies is observed. In γ-ray-scintillation spectroscopy this continuous spectra is referred to as the Compton edge. There is however a maximum possible shift namely the value obtained when ϕ=180°. This minimum value of $h\nu'$ is called the backscatter peak energy and determines the extent of the Compton edge as measured from a total energy peak. The most important feature of Compton scattering from an application standpoint is that it ignores the nucleons and is primarily an electron counter.

If the gamma energy is sufficiently high additional processes become possible. The one of greatest interest for diagnostic purposes is pair production. In the field of a charged particle a photon may be totally absorbed and a positron-electron pair emitted. A minimum eneergy of 1.02 Mev is required for this process to occur. Pair production begins to be noticeable at about 1 Mev and dominates over Compton scattering at E∿5-10 Mev. Because the process

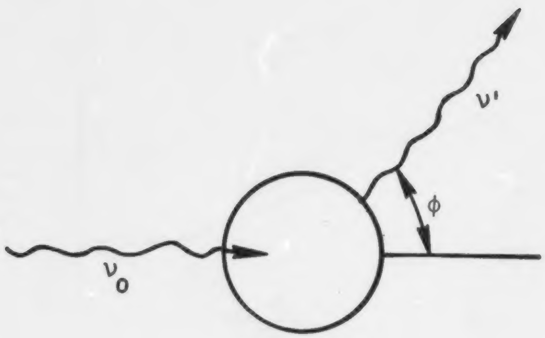


Figure 1. Compton effect geometry

usually involves the atom nucleii's electric field the cross section is dependent on the particular nucleii and typically increases as Z^2. At still higher energies additional processes are possible but are not of interest to current discussion.

As stated earlier the three important interactions dominate attenuation. By way of illustration of the magnitudes Figure 2 shows their relative magnitudes in cm^2/g Air.

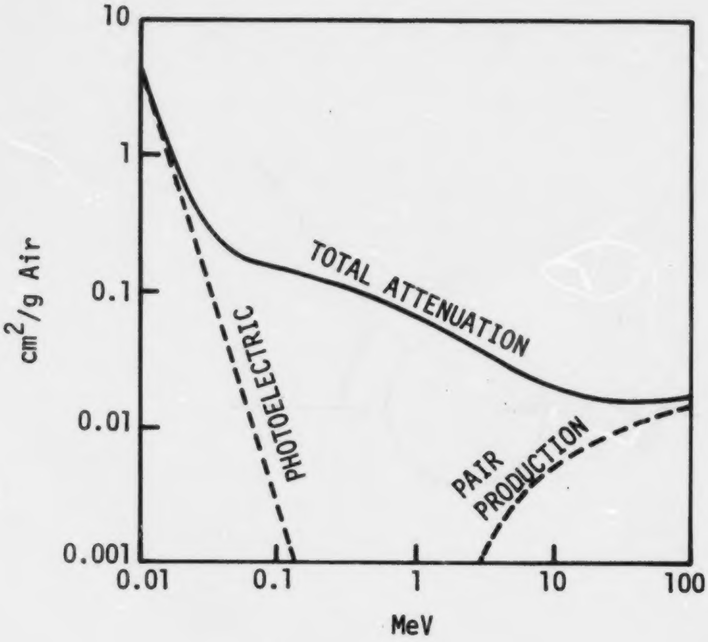


Figure 2. Mass attenuation coefficients for photons in air. Note that the total attenuation is almost entirely due to Compton effects in the intermediate energy range.

This figure illustrates all the comments made about relative importance of the processes. It also shows the relative magnitudes of the absorption. In particular note the high cross sections at low energy as this will later be important in the realization that X-ray fluorescence only probes surface layers. On the other hand for photons $\gtrsim$ 1 Mev substantial penetration thru thick material layers makes it possible to probe into macroscopic volumes of coal.

2.1.1.3 Neutron Matter Interactions

The neutron-matter interaction is quite different from the γ-ray matter one and thus requires a separate discussion. Like the γ-ray matter interaction it is convenient to divide the interaction types into inelastic and elastic cases. The neutrons themselves are classified by kinetic energy. Those with energies greater than 0.5 Mev are considered fast and those less than 0.5 Mev are considered slow. A more detailed classification scheme is also sometimes used as follows:

Table 4. CLASSIFICATION OF NEUTRONS BY ENERGY LEVEL

∿ 0.25 ev	Thermal
∿ 0.2 ev	Epithermal
∿ 0.4 ev	Cadmium
∿ 0.6 ev	Epicadmium
1-10 ev	Slow
10-300 ev	Resonance
500 ev-0.5 Mev	Middle
> 0.5 Mev	Fast
> 20 Mev	Ultrafast

The simplest type of interaction is just an elastic collision of a neutron with an atomic nucleus. The problem is easily treated by classical mechanics and the results basically indicate that the most effective energy transfer occurs when a neutron strikes a nucleus with a mass approaching that of the neutron. More quantitatively it is possible to calculate the average value of the quantity obtained from the expression:

$$\xi = \ln \left(E_0/E_1\right) \qquad (15)$$

where

ξ = logarithmic decrement of energy

E_0 = initial neutron energy

E_1 = energy after on collision

It can be shown that

$$\langle\xi\rangle = 1 + \frac{(A-1)^2}{2A} \ln \left(\frac{A-1}{A+1}\right) \qquad (16)$$

where

A = atomic mass of the target

For a neutron to slow from an energy of E_i to an energy E_f requires $[\ln (E_i/E_f)]/\xi$ collisions. Table 5 illustrates some typical values. This table shows that elastic neutron scattering is strongly dominated by low atomic number elements. Notice that if the scattering is evalued on a per mass basis rather than per atom, the low A values are even more dominant. As will be discussed later, this behavior can be utilized to detect moisture via the hydrogen induced scattering and is also a very important consideration in selecting shielding materials.

Table 5. NEUTRON SCATTERING PROPERTIES OF NUCLEI

Element	A	ξ	Number of collisions from 10 Mev to 0.025 ev
Hydrogen	1	1.0	19.8
Helium	4	0.425	46.6
Carbon	12	0.158	125.0
Sulfur	32	0.061	325.0
Iron	56	0.035	566.0

In addition to the elastic (n,n) type collisions which have been described above several types of important inelastic collision processes are possible. The most important possibilities of interaction with a nucleus are as follows:

1. The nucleus is excited to a higher energy level and returns to its ground state by the emission of one or more photons.
2. The neutron is captured and forms a compound nucleus. In some cases this new nucleus is in an excited state and decays to the ground state via the emission of γ-rays. This process is referred to as radiative capture and is represented by the symbol (n,γ).
3. The neutron is captured and another elementary particle is emitted.

4. Additional processes such as fragmentation and fission of the compound nucleus may also occur.

The relative probabilities of those processes are highly dependent upon both the nucleus involved and upon the energy of the neutron. In the current work the neutrons will typically have a fairly low energy and the atomic weight of the target nucleii will be low. Under those conditions the (n,γ) processes are usually the most important. Furthermore, the cross-sections for such reactions are typically largest for the slowest neutrons and vary approximately inversely with the neutron velocity. Thus, those neutrons that have been slowed to near Boltzman room temperature velocities (thermalized) dominate the inelastic reactions.

2.1.2 Activation Analysis Instruments (Ref. 7-12)

Inelastic neutron scattering can be effectively utilized for elemental analysis. Prompt gamma radiation associated with thermal neutron capture is especially useful. Figure 3 shows how the technique is employed. A suitable neutron source such as Californium 252 is utilized to provide a suitable neutron flux. These neutrons are thermalized and diffuse through a substantial probe volume of material. Occasionally a neutron interacts with a nucleus via an (n,γ) reaction. The energy of the promptly emitted gamma ray is characteristic of the energy level structure of the nucleus and can be used to infer the element's presence. Scattered gamma rays are detected by energy sensitive scintillation crystals, usually Tl activated NaI. The resultant signals are analyzed to determine the gamma ray energy spectrum and the energy distributions utilized to infer the elemental composition.

Figure 4 shows a typical spectrum obtained by Hall et al. To understand this spectrum it is first necessary to appreciate how a scintillation spectrometer works. Basically it consists of a scintillator material, a photomultiplier, and a pulse height analyzer. The function of the scintillator is to convert the gamma ray energy to visible radiation. This visible radiation is then converted to an electrical pulse and amplified by the photomultiplier. Each gamma ray produces an electrical pulse with a height ideally linearly related to its energy. The pulse height analyzer sorts pulses with respect to their amplitude and thus forms a histogram of the energy distribution as shown in Figure 4.

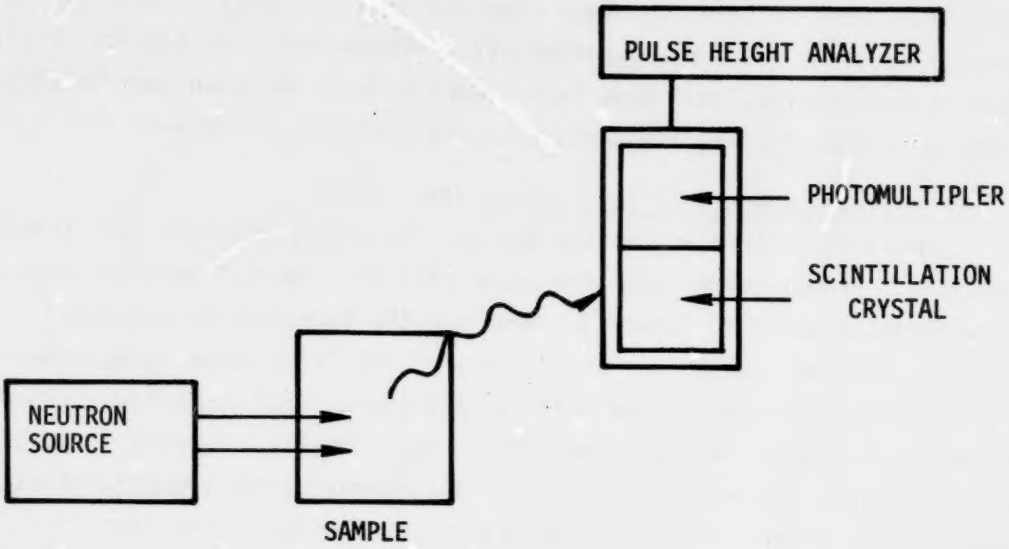

PULSE HEIGHT ANALYZER
PHOTOMULTIPLER
SCINTILLATION CRYSTAL
NEUTRON SOURCE
SAMPLE

Figure 3. Thermal neutron capture gamma ray analysis experimental configuration

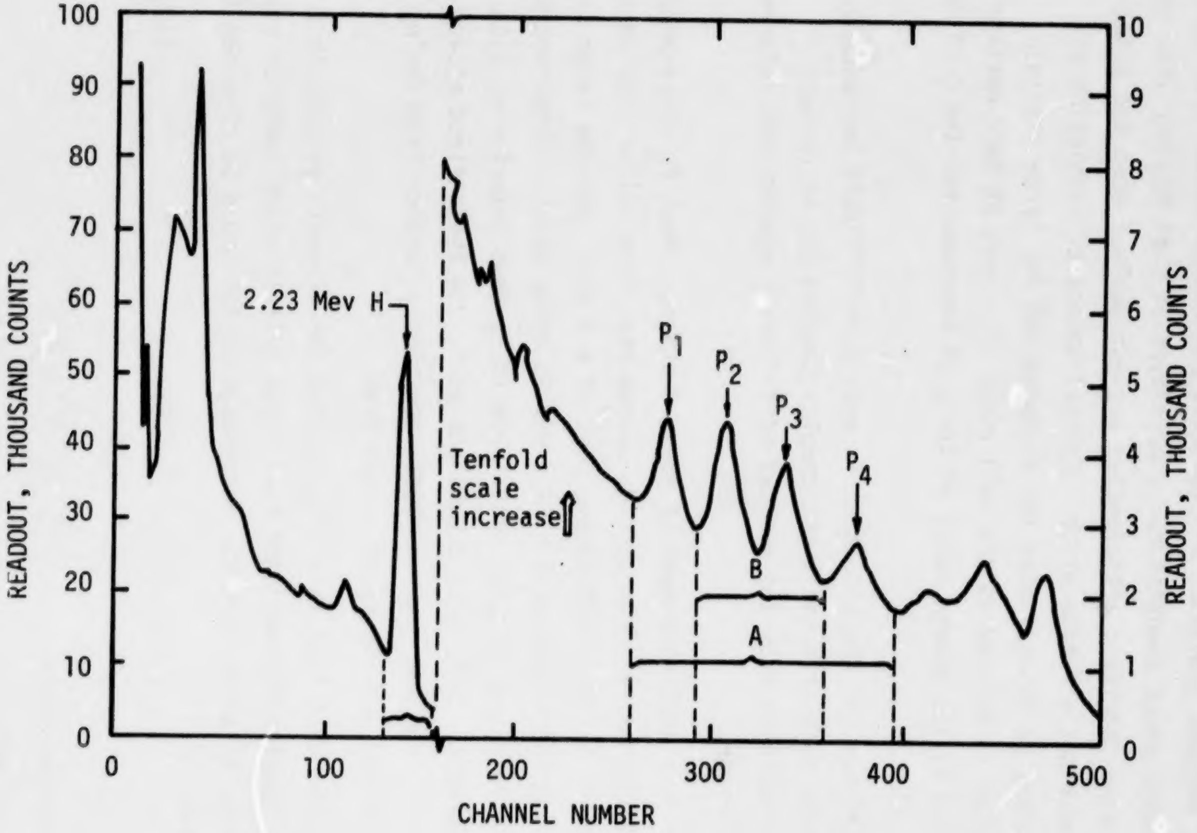


Figure 4. Gamma ray spectrum of coal measured with Cf-252 source and 6- by 7-inch NaI detector

Even monochromatic γ-rays unfortunately produce complicated scintillation spectra. In addition to a total absorption peak, they produce both Compton continuums and for energies above 1 Mev pair production peaks. Furthermore, because positrons or electrons can escape rather than being detected, escape peaks downshifted by multiples of 0.51 Mev may also appear. Finally, because intrinsic efficiencies are not perfect even the total absorption peak has a finite width. Typical values of resolution are highly dependent on crystal size and approach 10% for large crystals. Here resolution is defined as the full width of a peak at half maximum energy divided by the energy value of the peak measured for the 0.66 Mev γ-ray of Cs 137.

For real spectra the situation is even more difficult because many different peaks each with their own complex spectra may be present. Ambiguities resulting from the overlap of different spectra are referred to as interference.

Figure 4 illustrates many of these features. Peak P_3 corresponds to the 5.4 Mev gamma ray from sulfur. Gamma rays from sulfur also contribute to P_2 which is the first escape peak at 4.9 Mev. For the large crystal employed the second escape peak at 4.4 Mev is quite minor. Unfortunately, 4.9 Mev gamma rays from Si also contribute to P_2 thus interfering with the sulfur measurement. They also contribute to P_1 via their first escape peak. Finally, iron and other elements contribute further interfering signals at 6.0 Mev and its first escape peak.

Martin and Hall have carefully modeled the elements present in a typical coal sample and concluded that these interferences could be compensated for by assuming that the percentage sulfur could be obtained from the expression:

$$\%S = K\ (B-A/2) \qquad (17)$$

where

%S = percent sulfur
K = constant
B = area under inner two peaks
A = area under all four peaks

They tested this approach both experimentally and theoretically and found it to be fundamentally sound.

It is also possible to infer other elements by activation analysis. For instance the 2.23 Mev peak shown in Figure 4 is due to hydrogen and as stated earlier, peaks due to Si and Fe are also readily observed. Table 6 lists some analytical sensitivities for thermal neutron capture gamma rays as tabulated by D. Duffey et al. Sensitivity is expressed as

$$S = I\sigma/A \qquad (18)$$

where

S = sensitivity

I = number of gamma rays per 100 neutrons captured

σ = neutron absorption cross section in Barns

A = atomic mass

It must be appreciated that it is not practical to resolve all those lines but the possibility of obtaining further information is clearly present.

Table 6. ANALYTIC SENSITIVITIES FOR THERMAL NEUTRON CAPTURE

Element	Energy (Mev)	Sensitivity ($I\sigma/A$)
C	4.95	0.019
N	6.32	0.089
	5.27	0.136
Na	6.40	0.592
	3.98	0.501
	3.59	0.402
Mg	3.92	0.10
Al	7.72	0.175
Si	6.38	0.072
	4.93	0.402
S	5.42	0.678
	4.87	0.132
Ca	4.42	0.116
Fe	7.65	1.04
	7.63	1.27
	6.02	0.379
	5.92	0.389

2.1.3 Gamma Ray Density Gages (Ref. 13-15)

For a homogeneous material of thickness L and attenuation coefficient μ (cm^{-1}) the simple expressions discussed in Section 2.1.1.2 imply that if a collimated monochromatic gamma ray flux I_0 is incident upon the material then the transmitted flux is obtained from the expression:

$$I = I_0 e^{-\mu L} \qquad (19)$$

Thus, if I and I_0 are measured the quantity μL can be calculated:

$$\mu L = \ln \frac{I}{I_0} \qquad (20)$$

This approach is the basis of virtually all gamma ray density gauges.

Even for homogeneous materials and mono-energetic gamma rays there are limitations to the above analysis. These equations assume that only unscattered gamma rays are measured. In practice this idealization is not achieved. To even approach this situation would require an energy spectrum analysis of the detected radiation and a computer analysis of the peak area to subtract scattered radiation. Furthermore, real gamma ray sources are only approximately collimated so that angular variations may also influence the results. These complications are normally reduced by doing in situ calibrations so that to first order they are included in the system normalization.

Although the above discussion concerned only homogeneous materials, it is possible to extend the results to inhomogeneous ones. In particular if the energy of the gamma ray source is judiciously selected it can be shown that the product μL is a direct measure of the amount of mass interposed between the incident and transmitted flux. As previously discussed for gamma ray energies of order 0.5 - 1.5 Mev and low atomic weight elements the attenuation is dominated by Compton scattering. This means that the product μL is directly proportional to the number of electrons in the material volume. The following equations describe the situation:

$$N_e = A N_0 Z \qquad (21)$$

where N_e = number of electrons per unit volume

ρ = average density

Z = average atomic number

A = average atomic weight

N_o = Avagadro's number

$$\mu = f(E)\, N_e \tag{22}$$

where

μ = attenuation coefficient

$f(E)$ = energy dependent, material independent scattering function

= KE = const for a particular energy

The mass contained in a unit area slab of thickness L is obtained from

$$m = \rho L \tag{23}$$

The ratio of the quantity μL to this mass can be obtained by substitution into the above equations and is equal to

$$R = \frac{f(E)\, N_o\, Z}{A} \tag{24}$$

Thus the only material dependence in this ratio arises from the Z/A term. Table 7 shows that with the notable exception of H Z/A is virtually independent of material for low atomic number constituents. Thus the product μL is a direct measurement of the interposed mass independently of its composition.

Table 7. Z/A VALUES

Atom	Z	A	Z/A
H	1	1.008	0.992
C	6	12.01	.500
O	8	16.00	.500
S_i	14	28.09	.498
S	16	32.06	.499

The mass fractions associated with H atoms may induce some errors into density measurements but these usually only amount to a few percent and to the extent that hydrogen fractions are constant can easily be absorbed into the calibration. The only case where significant problems may arise is the measurement of low density solids in a water slurry. In this case the effects can be substantial.

The trade-offs associated with designing a gamma ray density measurement system are best appreciated by performing standard error analysis.

Let S_0 = the signal obtained with no interposed material in the probed volume

S_1 = the signal transmitted through the sample

then

$$\mu L = \ln \frac{S_0}{S_1} \tag{25}$$

Differentiating yields:

$$d(\mu L) = \frac{dS_0}{S_0} - \frac{dS_L}{S_L} \tag{26}$$

for independent measurements of S_0 and S_L the fractional uncertainty in μL is obtained by standard techniques:

$$\frac{\sigma_{\mu L}}{\mu L} = \frac{1}{\mu L}\sqrt{\left(\frac{\sigma S_0}{S_0}\right)^2 + \left(\frac{\sigma S_L}{S_L}\right)^2} \tag{27}$$

where the σ quantities denote standard deviations for the subscripted quantities. On this basis it appears advantageous to make μL as large as possible. However, the transmitted signal decreases exponentially with μL thus μL can't be too large or the statistical uncertainty in S_L will be large. This trade-off is integrally related to the γ source size and the thickness of the material being measured. A numerical example will be discussed in the applications section.

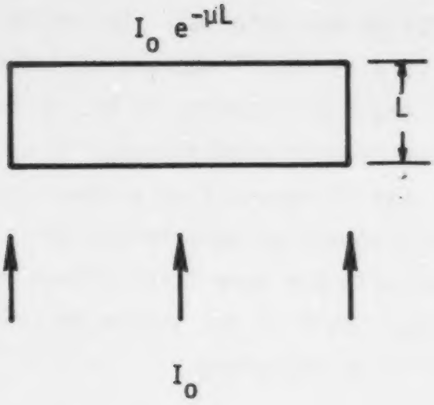
The utilization of the technique to assess coal flow also may be influenced by spatial inhomogeneity of the material. It can be shown that if a material contains inhomogeneously distributed regions of low density across the path of the gamma rays that the non-linearity of the technique will systematically lead to underpredictions of mass attenuation. The example of Figure 5 illustrates the situation. Case 1 consists of a simple homogeneous uniform slab with thickness L. The transmitted beam intensity is evidently $I_o\ e^{-\mu L}$. Case 2 consists of a scatterer with the same total volume and frontal area as in case 1 but with two thicknesses. Half of the sample is L-X thick and half is L+X thick. The transmitted radiation is therefore:

$$\frac{I_o}{2} e^{-\mu(L-X)} + \frac{I_o}{2} e^{-\mu(L+X)} = I_o\ e^{-\mu L} \cosh \mu X \qquad (28)$$

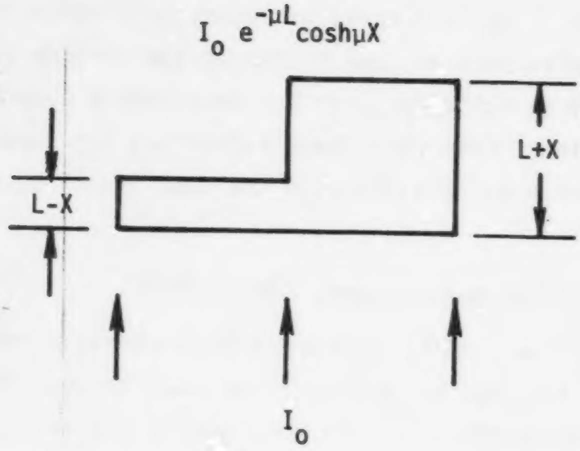
Cosh μX is always greater than 1 and approaches $e^{\mu X}$ for large values of μX. Thus the case 2 situation would lead to an underestimate of the amount of attenuating material present. In the extreme case when $\mu X >> 1$ the fractional error approaches X/L. It is clearly necessary to minimize such effects for very inhomogeneous products such as coal by making the mixture as uniform as possible. This can frequently be achieved by either integrating over a large area or over a long period of time. Even when these techniques are successful it is still desirable to perform a calibration with the coal itself to normalize out such systematic errors.

2.1.4 Neutron Moisture Measurements (Ref. 16-19)

Fast neutrons are readily produced with continuous energy distributions in the range of 1 to 6 Mev by utilizing radioactive sources such as 210 Po-Be or 252 Cf. If such neutrons are incident upon a medium, a portion of the neutrons are scattered and slowed down to thermal energies through a series of elastic collisions with the target nucleii. As described in Section 2 , this process is strongly dominated by light nucleii particularly hydrogen. Hydrogen not only is more effective at absorbing energy but also has a high collision cross-section. For instance, representative cross-sections for C and H atoms are 4 and 20 X 10^{-24} cm^2, respectively. Furthermore, according



CASE 1


$I_o\ e^{-\mu L} \cosh \mu X$
L-X
L+X
I_o

CASE 2

Figure 5. Inhomogeneity effects upon gamma ray transmission

to Table 7 hydrogen is 6 times more effective than C at transferring energy per collision. Thus, a hydrogen atom is approximately 20/4 x 6 = 30 times more effective at slowing fast neutrons than a carbon atom. On a weight basis the ratio is even more striking and becomes 360.

This strong preferential scattering by hydrogen can be utilized to infer hydrogen content of materials by employing detectors sensitive only to low energy neutrons. The approach is to direct a beam of high energy neutrons into the material of interest as shown in Figure 6 . Typical penetration depths of order 0.5 m are achieved. Thermal neutron detectors mounted nearby detect those neutrons which have been thermalized and nearly backscattered. The primary source of such neutrons is thermalization by hydrogen atoms and the measured signals are proportional to the amount of H present.

In some cases it is thus possible to infer moisture content once the hydrogen content is known. Unfortunately, this is not always the case because this method does not distinguish the chemical state of the hydrogen. Thus in the case of coal it is necessary to independently determine the hydrogen content of the dry coal before a moisture determination can be made. Under favorable circumstances when only one type of coal is utilized, this may be practical but in cases where different types are involved it may prove impossible to separate the intrinsic and moisture contributions.

2.1.5 X-Ray Fluorescence (Ref. 20-24)

If a target material is irradiated with high energy X-rays, it emits fluorescent radiation with an energy spectrum consisting of discrete lines. The discrete spectrum energies are characteristic of the energy level structure of the scattering atoms and allow a determination of the elements present in the target. Figure 7 shows the general classification scheme utilized to describe the transitions responsible for a given line. For example, when a K electron is knocked out of an atom, another electron can replace it giving rise to characteristic K series emission lines. Most X-ray fluoresence applications are based upon K or L lines.

In general X-ray fluorescence becomes an easier technique to apply as the atomic number of the atom of interest increases because atoms with larger atomic numbers produce characteristic X-rays of higher frequency. It was found empirically by Moseley that the characteristic X-ray frequen-

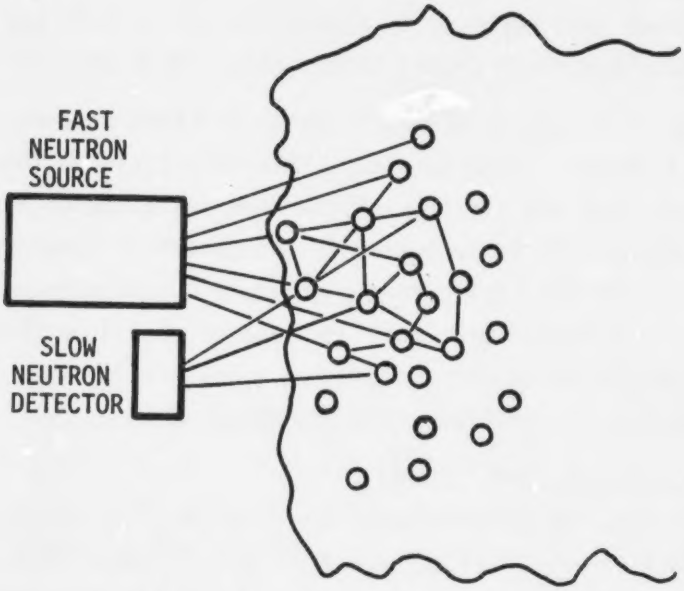
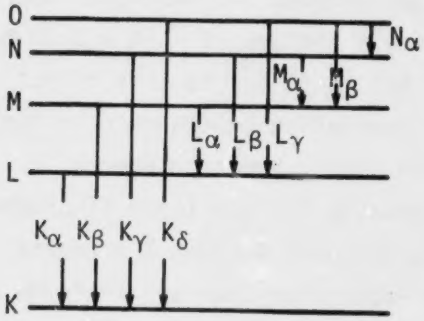

FAST
NEUTRON
SOURCE
SLOW
NEUTRON
DETECTOR

Figure 6. Principle of neutron moisture meter



O
N
M
L
K
Nα
Mα
Mβ
Lα
Lβ
Lγ
Kα
Kβ
Kγ
Kδ

Figure 7. Term scheme, showing the origin of the X-ray spectra of the elements.

cies are well fitted by the function:

$$\nu = K(Z-\sigma)^2 \tag{29}$$

where ν is the characteristic frequency, Z is the atomic number, and K and σ are constants common to all elements but different for the various lines ie. $K_{\alpha 1}$, $K_{\alpha 2}$ etc. At low photon energies the cross section for a given atom varies as $(\nu^2)^{-7/2}$. Thus roughly speaking the penetration depth of a characteristic X-ray into an arbitrary material varies as Z^7. Evidently low Z characteristic X-rays are much more readily absorbed than high Z ones. There is another experimental difficulty associated with the excitation of the light elements. It is called fluorescent yield. The problem is that for low atomic number elements, K emission radiation may knock out an L electron rather than leaving the atom. This process is called the Auger effect and becomes increasingly important for low atomic number elements. For example, between Z = 30 and 15 the observed yield drops from approximately 45% to 5% due to this effect alone. Both this effect and the very low penetration depths make it impractical to utilize X-ray fluorescence for low atomic number elements.

Figure 8 shows schematically how X-ray fluorescence is used to analyze materials for the presence of high Z elements. The first requirement of the system is an excitation source. In large analytical instruments this may consist of an electron beam or an X-ray tube. In small portable devices isotopic X-ray sources have proved to be more convenient. As this source bombards the target a portion of the target atoms emit characteristic X-rays. Part of the fluorescent radiation is received by the detection system and some sort of energy separation scheme employed. In analytical instruments which have very high sensitivity, typically a crystal system utilizing Bragg scattering is employed and a detector only processes those X-rays dispersed at the appropriate angle. Somewhat simpler but less sensitive systems have successfully utilized material filters instead. The detector utilized is usually a simple proportional or ionization counter which produces a discrete count for each X-ray detected.

For purposes of quantitative analysis it is necessary to correlate the measured intensity of each line with the percentage composition of the specimen. This signal is related to a number of features of the measurement system response and geometry. It is however possible to control for

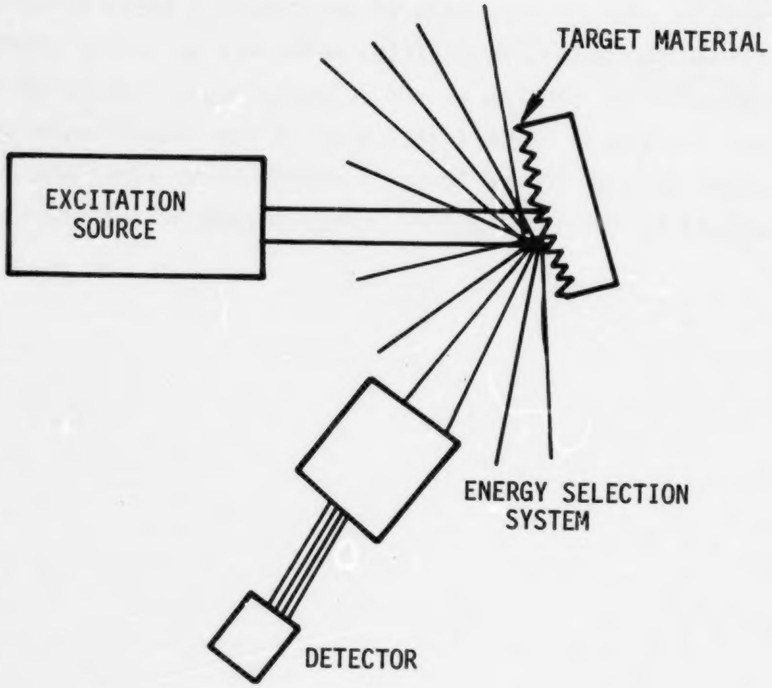

TARGET MATERIAL
EXCITATION SOURCE
ENERGY SELECTION SYSTEM
DETECTOR

Figure 8. X-ray fluorescence configuration

these factors so that the limiting feature is the matrix effect which varies with the sample composition. Matrix effects include both absorption and enhancement effects. The absorption effect is caused by the fact that both characteristic and primary X-rays must pass through increasing amounts of matrix material as penetration goes deeper into the sample. Enhancement is a further complication that occurs because characteristic fluorescent lines of some matrix elements may excite the characteristic spectra of the desired element. These effects are highly complex and dependent upon both chemical composition and physical form of the matrix. These effects make careful corrections for matrix composition necessary to obtain useful results. The attenuation problem is sufficiently acute that X-ray fluorescence techniques for atomic numbers less than 10 are almost never used and for atomic numbers between 10 and 20 it is necessary to eliminate air attenuation effects by utilizing either a vacuum path or purging with Helium.

2.2 FLOW MEASUREMENT INSTRUMENTS

2.2.1 Dry Coal Flow

Of the types of measurements considered in this report, this is the one which can be performed with the least difficulty, lowest cost, and greatest accuracy. In any total instrumentation system where the final output is mass flow rate of a coal constituent, such as carbon, ash, or sulfur, if the total mass flow measurement is that of a dry (i.e., non-slurry) coal stream, the total mass flow measurement should have a negligible impact on system error in a properly designed and operated system.

Measurement of dry coal flow rate does not differ in any important aspects from measurement of a large variety of other solids. The widespread need for solid flow measurement for everything from potatoes to iron ore has resulted in very accurate and reliable instrumentation. The most widely used measurement techniques can be categorized as static (i.e., batch) or dynamic, with the latter category subdivided into vertical motion techniques and horizontal motion techniques. Weight scales are means by which the static measurements are taken. Since weighing is the means by which raw materials have been bought and sold for thousands of years, there has been a corresponding great interest in accurate weighing techniques. In the context of our current interest, we need to note the following:

- Quantities of coal at least up to that contained in a typical railroad car can be weighed with very high accuracy (∿ .1% or better).
- As is discussed below, static weighing of a given amount of material is the preferred means by which a calibration of a dynamic (continuous) system is obtained.

Flow measurements using static weighing techniques can be done on a batch, or semi-continuous, basis, such as having individual coal-carrying railroad cars, or trucks, momentarily come to rest on a static scale, or by having coal fed into a hopper, stop the flow, take a weight measurement, dump the coal, and then resume the feed. The development of instrumentation which can be used directly on conveyor belts has eliminated the need for batch weighing measurements other than for calibration purposes. Presented below is a background section on conveyor belt instrumentation (here termed weigh belt instrumentation), followed by a short section on techniques such as loss-in-weight, which apply to vertical flow systems.

2.2.1.1 Weigh Belt Techniques

The term "weigh belt", "belt scale", and "conveyor scale" are all used to describe the type of instrument shown schematically in its two most common configurations in Figures 9a and 9b. These instruments are used in conjunction with a conveyor belt of some sort which moves the material of interest between two points. The configuration in Figure 9a is generally used in conjunction with long conveyor belts whose primary purpose is conveyance, as from a coal stock pile to a power plant hundreds of meters away. The configuration in Figure 9b is normally used at the outlet of a hopper, so that the coal falls vertically onto the belt, and then the coal is conveyed only a short distance ($\sim$ 3 meters typical) before being unloaded. As far as the instrumentation system is concerned, the only significant difference between these two types of applications is the length of the belt. All common weigh belt instruments for either application have three features in common:

1. A sensing section of the belt, which is a specified length along which the contents being conveyed are continuously weighed, providing the $\frac{m}{\ell}$ term in Equation (1).
2. A device to measure linear belt speed through the sensing section, providing the $\dot{\ell}$ term in Equation (1).
3. An integrator to combine the two measurements to produce $\dot{m}_T$, the total mass conveyed since a specified starting time.

There are instruments in which these elements are done wholly by mechanical means. Most currently marketed instruments use a combination of mechanical and electronic devices, and a nuclear radiation technique is becoming popular for the weight measurement term.

The basic mechanical or electro-mechanical weighing technique is shown in Figure 10. The basic elements in the assembly are a continuous conveyor belt supported periodically along its length by idlers (cylindrical rollers) which are attached to a metal frame, a belt drive mechanism, one or more idlers or idler assemblies attached to a floating weigh bridge, a belt speed sensor either in contact with the belt itself or with one of the idlers, and a

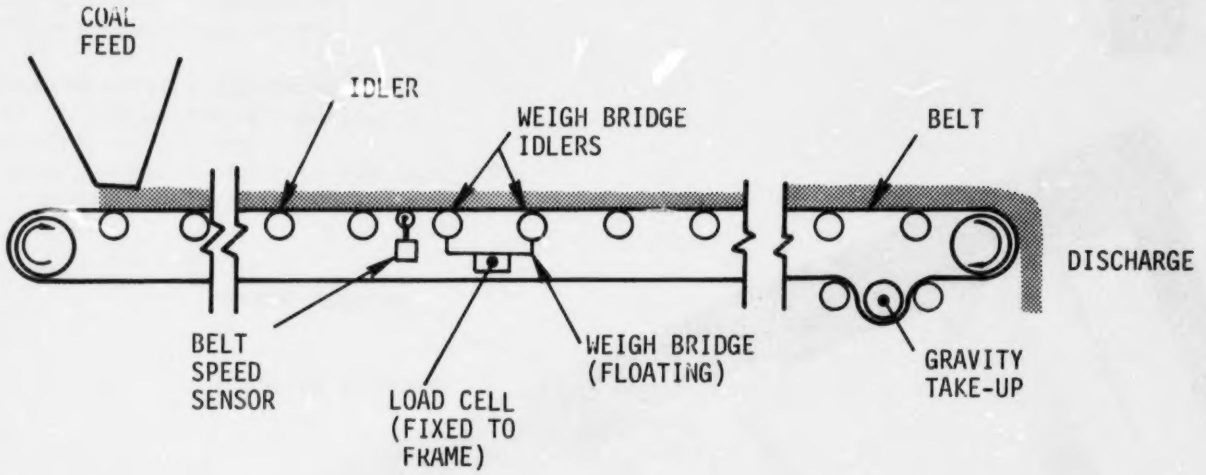

COAL FEED
IDLER
WEIGH BRIDGE IDLERS
BELT
DISCHARGE
BELT SPEED SENSOR
LOAD CELL (FIXED TO FRAME)
WEIGH BRIDGE (FLOATING)
GRAVITY TAKE-UP

Figure 9a. Weigh belt installation for long belt

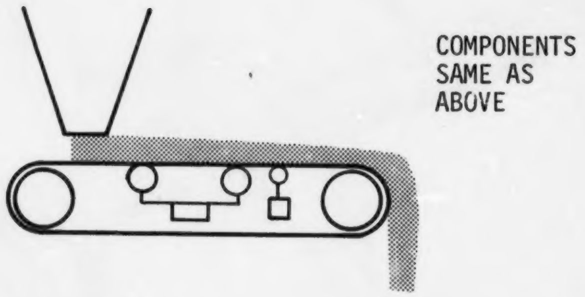
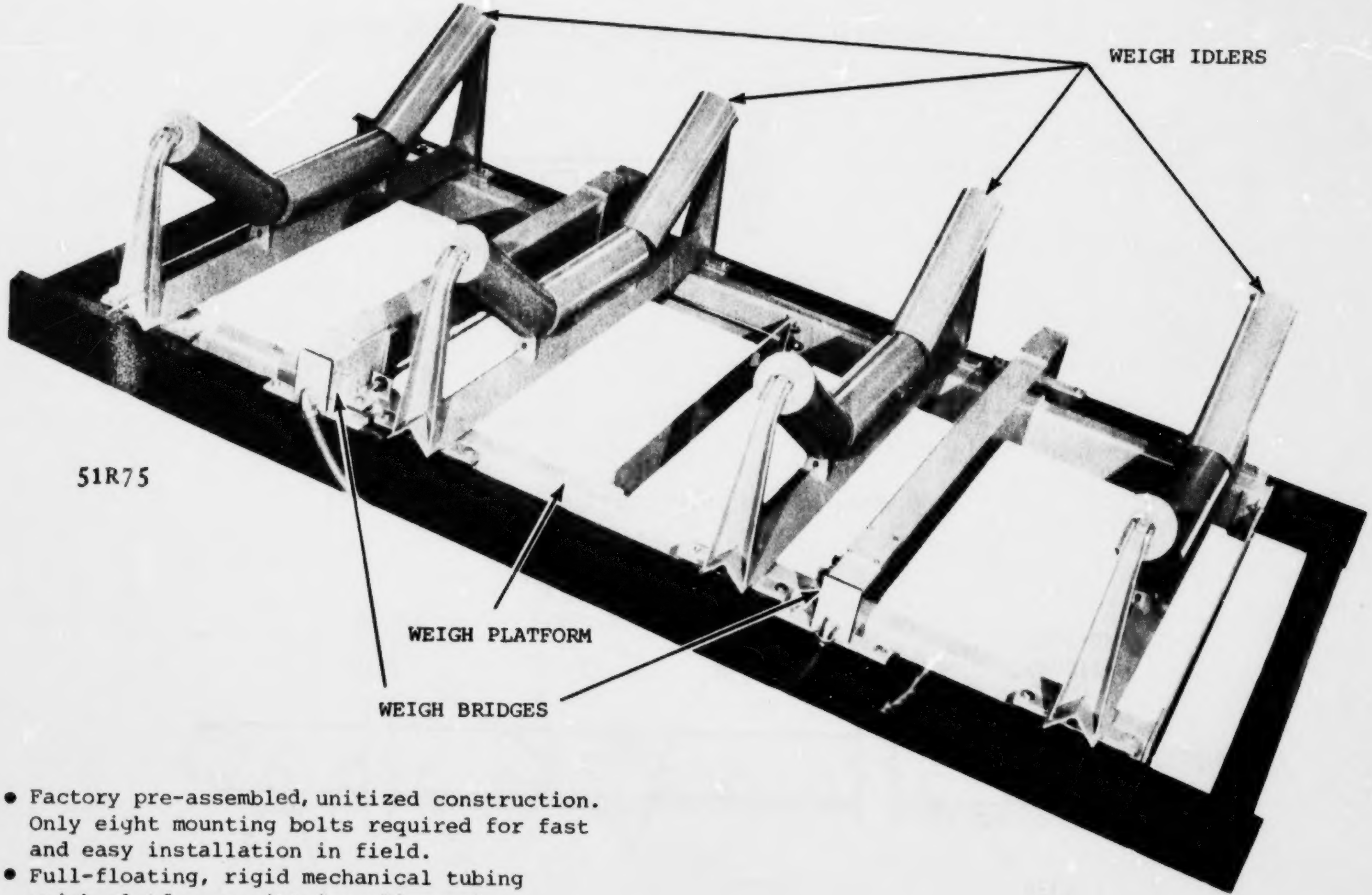

COMPONENTS SAME AS ABOVE

Figure 9b. Weigh belt installation for short belt

RAMSEY MODEL 10-4 WEIGHBRIDGE ASSEMBLY
(4 IDLER SUSPENSION SHOWN, ALSO AVAILABLE IN 2 AND 3 IDLER SUSPENSIONS)



- Factory pre-assembled, unitized construction. Only eight mounting bolts required for fast and easy installation in field.
- Full-floating, rigid mechanical tubing weigh platform--maintains alignment permanently.
- Four, super precision strain gauge load cells (with special temperature compensation) applied in tension--less than .001" deflection on weigh platform.

RAMSEY ENGINEERING COMPANY

1853 W. COUNTY RD C
ST PAUL MINNESOTA 55113
PHONE (612) 633-5150
CABLE ADDRESS RAMCO
TELEX 29-7001

Figure 10. Typical weighbridge unit

weighing device which senses the instantaneous weight of the floating weight bridge and the length of belt and its contents in the sensing region. In a strictly mechanical system, the weight of the "live" components are transmitted to a mechanical integrator via lever arms, pully and/or gears. Load cells are the most commonly used weighing device presently sold. All manufacturers contacted who deal in electro-mechanical mechanisms use one of a variety of types of load cell, sometimes in conjunction with a lever arm system, to sense weight. Belt linear velocity is typically determined in a digital manner by measuring the rotational speed of an idler which contacts the belt or that of a precision wheel which is held in contact with the belt by a spring loaded lever arm. The measurement is digital in that full rotations of a wheel, or partial rotations based on sensing teeth regularly spaced around the wheel circumference for higher resolution, are sensed as a function of time. This rotation rate measurement is transformed into a belt speed measurement by multiplying the rotational rates of the wheel by the wheel radius.

It is appropriate in terms of report organization to present the physics of nuclear weighing devices along with that of other nuclear radiation techniques. This is done in Section 2.1. For the purposes of this section, it is appropriate to simply state that in a nuclear radiation weighing device, a nuclear radiation source sends out gamma rays, a percentage of which are absorbed by any matter placed between the source and the detector. The gamma ray attenuation is proportional to the amount of mass placed between the source and the detector. This mass normally consists of a very short (compared to the electro-mechanical instruments) length of conveyor belt and the material on it, and, usually, a part of the fixed framework below the belt. In principle, then, a nuclear scale acts just the same as an electro-mechanical one, in that it measures m/ℓ, and it must deal with the same type of tare, i.e., the belt and some portion of fixed structure. Here are two major differences between the two approaches: The obvious one is that the weight sensing approaches are quite different; the other is that the nuclear scale has no mechanical contact with the conveying system, whereas an electro-mechanical device must be mechanically integrated and in physical contact with the conveying system. The latter may influence instrument selection in retrofit or unusual applications.

The aspect of weigh belt use which it is appropriate to treat in this section is calibration. Both electro-mechanical and nuclear scales have belt and framework weight to be dealt with as tare in addition to the weight of the coal itself. A partial list of possible causes of calibration shifts is:

- Change in belt tension
- Material sticking to belt and being weighed more than once
- Belt erosion
- Change in density and/or positional distribution on the belt of material being conveyed
- Change in material loading
- Change in composition of material being conveyed (applies to nuclear scale)
- Accumulation of coal dust on sensitive portions of mechanism
- Sensor drift as a function of ambient atmospheric conditions and time.

Several of these are rather easily eliminated through proper equipment design, installation, and operation (belt tension, material sticking, distribution and loading, dust accumulation, atmospheric condition changes). Others must be dealt with by periodic recalibration.

To achieve optimum accuracy, we need to be concerned about two aspects of system design and operation; material loading on the belt and method of calibration. In each case, there will usually be cost/accuracy trade-offs to be considered. The feed rate of material, $\dot{m}_T$, as noted in Equation (1), is the product of the material loading on the belt, m/ℓ, and the belt speed, $\dot{\ell}$. Either or both can be varied to provide a desired total flow. The belt speed measurement accuracy is essentially independent of the belt speed itself, i.e., it is a "percent reading" type accuracy. By contrast, it is normally the case that load cells and nuclear scales tend to behave as "percent full scale" accuracy instruments, so that significant changes in belt loading will produce larger random errors. In addition, changes in material loading will also introduce non-linearities in the calibration curve of the weighing device (output vs m/ℓ), which could be eliminated only through meticulous calibration over a wide loading range. Consequently, optimum accuracy will be obtained when the material loading is held constant at a specified level and belt speed is used as the primary variable to obtain desired variations in $\dot{m}_T$. The other benefit of operating in this mode is that the system time response is shorter for a variable speed belt system, since the delivery rate changes concurrently with changes in belt speed. In a constant belt speed system, there is an inherent delivery delay time of $\ell_B/\dot{\ell}$, where ℓ_B is the length of the belt between the loading and unloading points.

Three methods of system calibration are in general use at present: Static calibration, dynamic calibration with chains, and dynamic calibration with material being conveyed. It must be emphasized that only the last method constitutes a true system calibration. In this method, a known quantity of material, an established by static weighing either before or after conveyance along the belt, is conveyed past the instrument. This is a true in-situ calibration, and is the most time consuming and therefore most expensive method of calibration. A less rigorous method of calibrating electro-mechanical systems is to use a calibration chain of known m/ℓ affixed to the belt. The objection to this common technique is that the chain will not load the belt in quite the same manner as the actual material, producing systematic errors. In the static calibration method which is becoming popular because it is quick and inexpensive, a known dead weight is attached to the load cell in an electro-mechanical system, or a metal plate of known attenuation properties is placed between the source and detector in a nuclear scale system. This is not a system calibration - it is merely a single point load sensor check. Its primary value would be as a quick sensor check between material calibrations. It should not be used in lieu of material calibrations.

The current status of weigh belt instrumentation, including manufacturers, type of equipment, accuracy and cost data, is presented in Section 3.2.1.

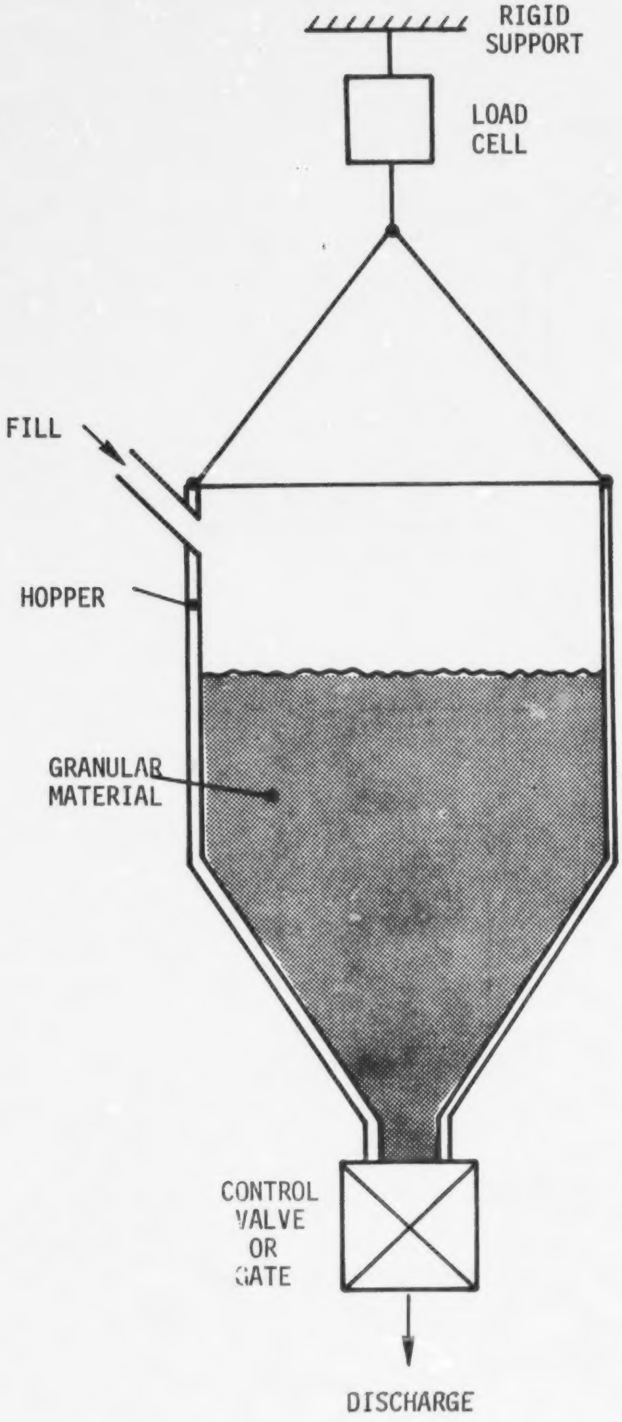
2.2.1.2 Vertical Flow Techniques and Miscellaneous Techniques

The low cost, accuracy, and reliability of weigh belt techniques have resulted in their "cornering the market" for high flow rate dry granular material bulk flow measurement. Some alternate techniques are mentioned below. These are usually employed for "hard to handle" materials (coal is an "easy to handle" material) or are used in situations where a conveyor belt is not practical for some reason.

Conveyor belts must operate at an angle close enough to the horizontal that the material will not slide. Under some circumstances, it may be necessary or desirable to have a measurement system through which the material passes vertically. Two such techniques are loss-in-weight systems and what will be referred to here as a solids turbine.

A loss-in-weight system is shown schematically in Figure 11. The basic components are a hopper, load cell, outlet metering valve or gate, and material feed line. Principles of operation are simple. With the outlet closed, material is fed into the hopper until a desired total weight is reached. The material feed is then stopped, and the outlet is opened to achieve a desired flow rate. The flow rate is determined by the change in the load cell reading per unit time. The load cell is often connected via a servo loop to the outlet controlling mechanism so that a desired flow can be maintained. When the load cell reaches a specified minimum reading, the outlet is closed and the procedure repeated. This approach involves more and bulkier equipment than a weigh belt for the same level of flow, and it is clearly a batch process rather than continuous. Due to the relatively wide range which the load cell must cover, the accuracy will generally not be as good as for a weigh belt installation using a comparable load cell. Best accuracy for a loss-in-weight system is about 1% of reading.

The solid turbine is shown schematically in Figure 12, and is directly analogous to a turbine motor used for fluid flow. While a paddle wheet is shown in the schematic for simplicity, actual devices use multiple helical blades, so that the turbine axis is vertical. The kinetic energy of the falling solid material impinging on the rotor blades causes the rotor to turn at a rate proportional to the solid mass flow. This is a viable technique for continuous flow measurement, but has not achieved the accuracies of weigh belt systems.


RIGID SUPPORT
LOAD CELL
FILL
HOPPER
GRANULAR MATERIAL
CONTROL VALVE OR GATE
DISCHARGE

PROCEDURE:

1. HOPPER IS FILLED (OUTLET CLOSED)
2. CONTROL VALVE IS OPENED TO DESIRED POSITION AND LOAD CELL OUTPUT VS. TIME GIVES MASS FLOW RATE
3. CONTROL VALVE IS CLOSED AND HOPPER REFILLED

Figure 11. Schematic of Loss-In-Weight system

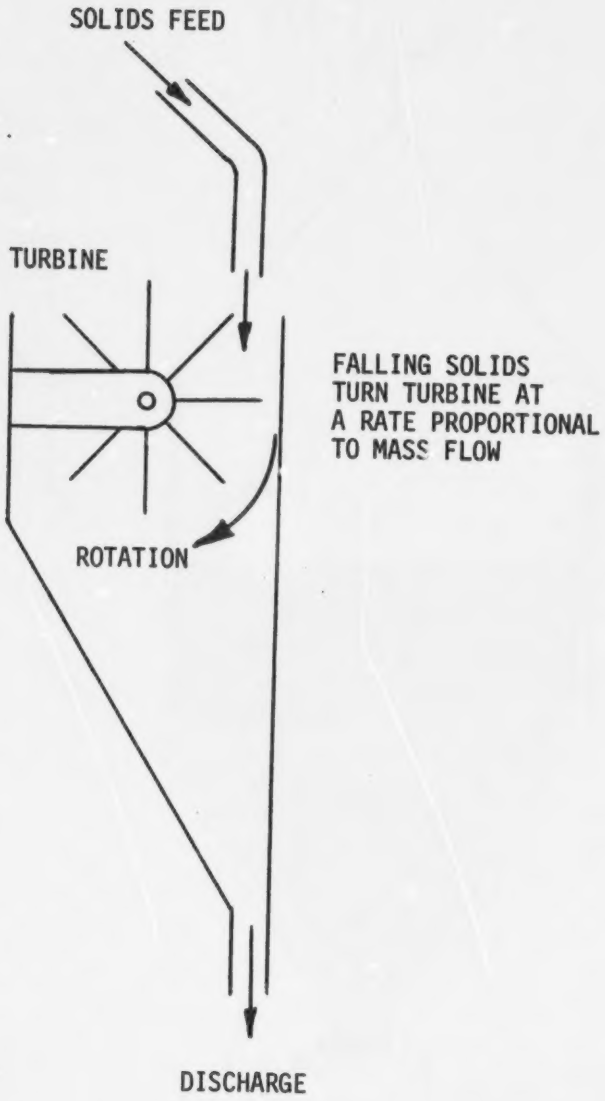

SOLIDS FEED
TURBINE
FALLING SOLIDS TURN TURBINE AT A RATE PROPORTIONAL TO MASS FLOW
ROTATION
DISCHARGE

Figure 12. Illustration of "Solids Turbine" concept

One final technique worthy of mention, but applicable only for rather low flow rates, is the screw feeder, shown in Figure 13. It is similar in concept to positive displacement metering pumps for fluids. Material from the hopper falls onto the screw, is conveyed along an annual passage, and then falls off the screw at the exit. For a given screw, feed rate is proportional to the screw rotation rate. A good feeder flowrate accuracy is about 5%.

2.2.2 Coal/Water Slurry Instruments

Coal/water slurry flow measurement is inherently more difficult than dry coal flow measurement, and will rarely be as accurate. The measurement is also complicated by the fact that there are inherently two parameters of interest: The total flow rate (both coal and water) and the percent coal in the slurry. This means in normal practice that two separate instruments are required - one for flow and one for coal content.

The general approach which has been taken to slurry flow measurement has not actually been an approach but rather an avoidance - this type of measurement is performed only when necessary. Slurry flow instruments all have one feature in common - they were originally developed for liquid flow application where the solids content in the stream is negligible. It is also fair to say that any flow device which is acceptable for cool/water slurry flow measurement would work more accurately and reliably if the flowing medium were water with only trace amounts of solids or non at all. Thus the coal in the slurry is, as far as the instrument is concerned, a contaminant, which tends to make its presence known by accumulating in undesirable places, acting as an abrasive, and/or obstructing signal paths.

For purposes of this report, instruments are being separated into two categories: Obstructionless (with respect to the slurry flow, the instrument behaves as an equivalent length of straight pipe) and intrusive (one or more instrument components are physically inserted into the flow stream). This distinction is being made from the standpoint of applicability - experience has shown obstructionless flow meters to be much more suitable for slurry flows, although some manufacturers claim that their intrusive devices are

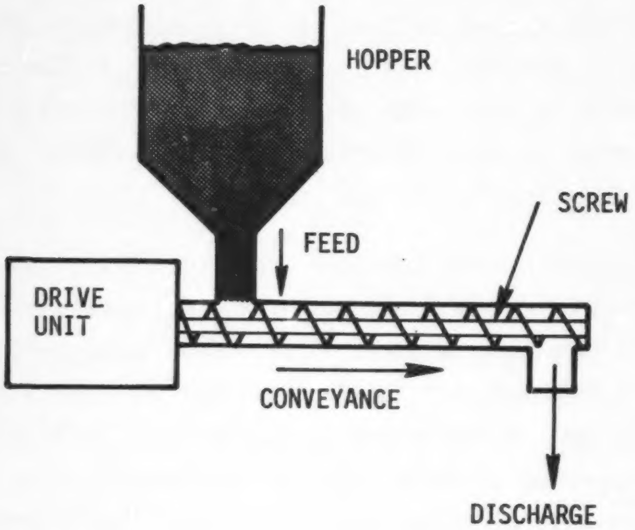

HOPPER
SCREW
FEED
DRIVE UNIT
CONVEYANCE
DISCHARGE

Figure 13. Schematic of screw feeder

acceptable for the present application. Both instrument categories are discussed below, followed by a discussion of a system consisting of a flow meter and density gage.

2.2.2.1 Obstructionless Flowmeter

2.2 2.1.1 Magnetic Flowmeter

As manufacturers are quick to point out, the magnetic flowmeter has been around, at least in concept, since the 1830's when Faraday attempted (unsuccessfully) a demonstration in the Thames River. Reference 25 notes that the first electromagnetic flowmeter patent was issued in 1915.

The magnetic flowmeter is shown schematically in Figure 14. Basic descriptions of its workings are presented in References 25-29. The operation principle is Faraday's Law of Induction, which may be stated as (Ref.26):

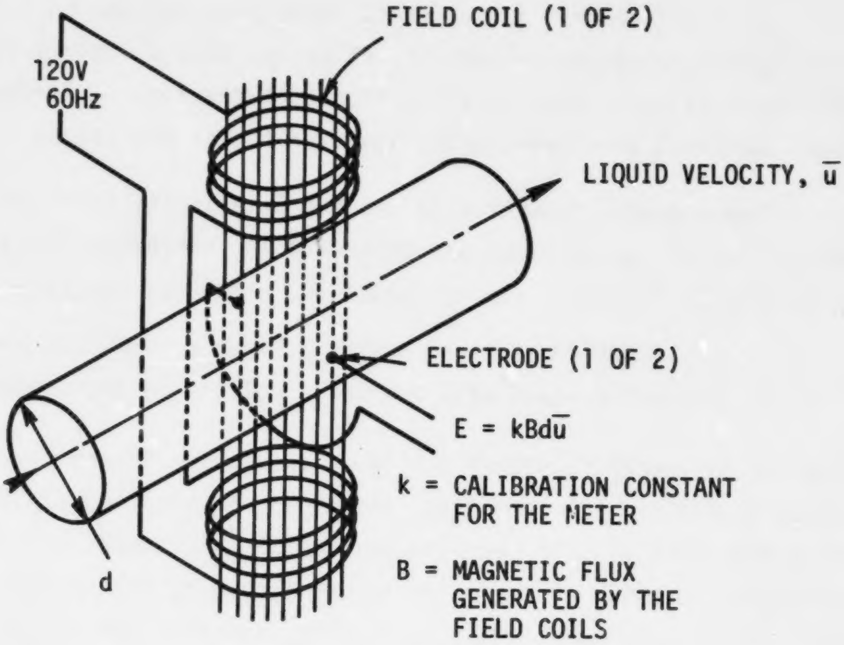
> "... motion at right angles between a conductor and a magnetic field will develop a voltage in the conductor".

The device itself is rather simple, although not inexpensive, consisting of a magnetic field across the pipe, and a pair of electrodes. The field lines, direction of flow, and the line between the electrodes form a mutually orthogonal system. The electrodes are typically mounted flush with the pipe wall, or in some cases are slightly recessed from the wall. The material being conveyed must have a minimum electrical conductivity for the meter to be able to operate (i.e., generate a voltage between the electrodes). Ordinary tap water has sufficient conductivity, so there is no problem with coal/water slurries in that regard. Performance of the instrument is described by the following equation:

$$E = KBd\bar{u} \tag{30}$$

where

E = emf produced between the electrodes, volts
K = calibration factor, dimensionless
B = magnetic flux density, volt·s/m^2
d = distance between electrodes (normally pipe I.D), m
$\bar{u}$ = slurry average axial velocity, m/s



FIELD COIL (1 OF 2)
120V
60Hz
LIQUID VELOCITY, $\bar{u}$
ELECTRODE (1 OF 2)
$E = kBd\bar{u}$
k = CALIBRATION CONSTANT FOR THE METER
B = MAGNETIC FLUX GENERATED BY THE FIELD COILS
d

Figure 14. Schematic of electromagnetic flowmeter, taken from Reference 25.

The desired outputs are volumetric flow and/or mass flow, given by

$$\dot{V} = \bar{u} A = \bar{u} \frac{\pi}{4} d^2 = \frac{\pi E d}{4KB} \tag{31}$$

where

$\dot{V}$ = slurry volumetric flow, m^3/s
A = pipe cross-sectional area, m^2

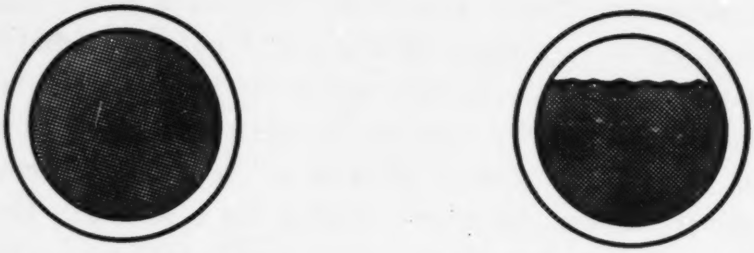
and

$$\dot{m}_T = \rho_{sl} \dot{V} = \rho_{sl} \frac{\pi E d}{4KB} \tag{32}$$

Equation (30) is very illustrative of the workings of this type of meter. The form of Equation (30) makes it clear that the magnetic flowmeter senses velocity — not volumetric flow or mass flow. This means that a separate density determination is required to obtain mass flow, as in Equation (32). Another not quite obvious but very important point is that the meter output will be essentially the same for constant average slurry velocity whether or not the pipe is full. This is illustrated in Figure 15. As long as there is a conductive path through the slurry between the electrodes, the flowmeter cannot distinguish between a full and a partly full pipe. This imposes the requirement on the system that the pipe always be full.

In a given setup, the calibration factor K in Equation (30) is established by in-place calibration (usually by dumping the slurry into a volumetric tank). The calibration factor is not subject to change due to changes in slurry properties such as conductivity (as long as the minimum conductivity requirement is met), nor is it subject to changes in the coal/water ratio or coal composition. It is, however, subject to changes in flow profile. Equation (30) was derived from the case of an axisymmetric flow profile. Thus the flow as it goes through the meter may be uniform, partially developed (as long as it is axisymmetric) or fully developed (either laminar or turbulent) without causing a calibration shift. The following quote from Reference 27 describes meter performance in asymmetric flows:

> "... it is easy to show that a velocity variation along the electrode diameter, but with constant velocity along each vertical line (parallel to the flux lines), will produce significant error. Such



a. PIPE FULL

$\overline{u}$ = 2.0 m/s

METER READING = 2.0 m/s

RESULT: CORRECT VOLUMETRIC FLOW SENSED

b. PIPE PARTIALLY FULL

$\overline{u}$ = 2.0 m/s FOR ACTUAL SLURRY

METER READING = 2.0 m/s

RESULT: INCORRECT (HIGH) VOLUMETRIC FLOW SENSED

Figure 15. Illustration of magnetic flowmeter error due to non-full pipe

> a profile is farfetched. ... The author has been unable to produce errors discernible in a background scatter of ± 0.5 percent by any piping configuration, including a throttling gate valve 4 [pipe diameters] upstream from the electrode plane."

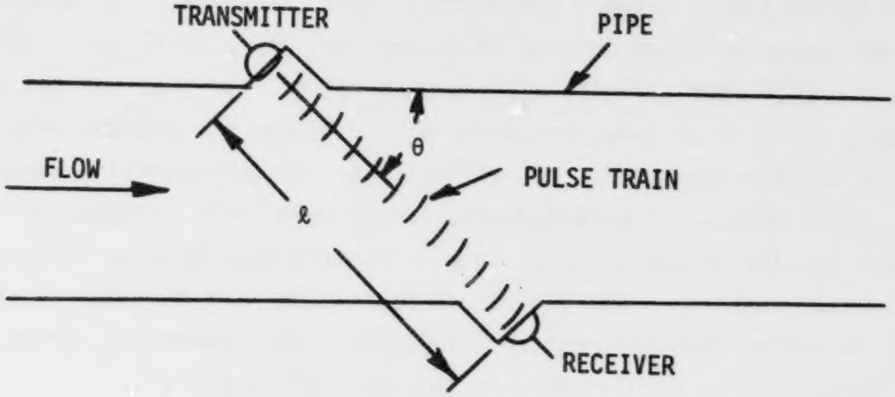
One source of velocity-related systematic error which we have not found treated in the literature is the error due to a net velocity differential between the water and the coal in the slurry. Fortunately, with respect to this error source (but unfortunate for density determination), the density difference between coal and water is small ($\sim$ 30%), so the velocity difference would tend to be small except for large coal particles. This differential will be a maximum for vertical flow. Vertical flow upward through the meter is often desired to insure that the pipe is full. If there is a significant velocity differential between the coal and the water, significant being 1% or more, the meter will register the average velocity of what is passing through it, but will give no indication of the coal/water velocity differential. The differential would have to be detected by comparing the density of the material in a volumetric tank to that in the flow line. If the latter is higher, it is an indication that the mean water velocity is higher than the mean coal velocity. This potential error source, then, must be handled through the calibration process.

Achievable accuracies for magnetic flowmeters are dependent on the electronics package. Typical manufacturer's specifications are ± 1% of reading over a 10 to 1 flow range or ± 0.5% of full scale, according to the customer's desires. As is shown below, this does not translate into 1% accuracy on the coal flowrate — that accuracy will not be as good due to density measurement errors.

2.2.2.1.2 Ultrasonic Flowmeter (Reference 30-31)

The most basic type of ultrasonic flowmeter would be as shown schematically in Figure 16. It consists of a source of high frequency pressure pulses and a detector on either side of a pipe, typically at a 45° angle with respect to the pipe axis. In the configuration shown in Figure 16, the transit time of a discrete pulse is given as

$$t = \frac{\ell}{(c + v_m)\cos\theta} \tag{33}$$


TRANSMITTER
PIPE
θ
FLOW
PULSE TRAIN
ℓ
RECEIVER

FLOW INCREASES PULSE TRAIN SPEED IN A LINEAR MANNER, AND IS SENSED BY DIFFERENCE IN PULSE TRANSIT TIME FOR FLOWING AND STATIC CONDITIONS.

Figure 16. Ultrasonic flowmeter schematic

where

ℓ = acoustic path length, m

t = transit time, seconds

c = speed of sound in the slurry, m/s

v_m = mean slurry axial velocity along the line between the source and detector, m/s

θ = angle between the pipe axis and the line between the source and detector, degrees

It will always be the case in coal/water slurries that $c \gg v_m$. Also, the mean velocity v_m along what is effectively a diameter, is not the same as the average velocity in the pipe, $\overline{u}$. These two parameters are related in a known way for the case of fully developed pipe flow by a function which is dependent only on the pipe Reynolds number:

$$\overline{u} = f\,(Re_p)\,v_m \tag{34}$$

where

f = functional relationship, dimensionless

Re_p = pipe Reynolds number

There are no devices on the market which use hardware corresponding to the technique described by Equation (33). Changes in the sound speed, c, due to concentration, composition, or temperature are typically of the same order as the slurry velocity, which would lead to very poor accuracy. Consequently, the normal hardware approach is to use two source/detector pairs, with one signal propagating upstream and one propagating downstream. Sinusoidal pressure pulse trains are then propagated in each direction, and the instrument output becomes a frequency difference which is directly proportional to v_m and is independent of c. This leaves us with three primary error sources: the frequency difference, the path length, and the relationship between v_m and $\overline{u}$. The last two sources should be minimized by in-place calibration, while the first is dependent upon the basic quality of the instrument itself and the slurry properties.

Like the magnetic flowmeter, the ultrasonic flowmeter is inherently a velocity measuring device — it does not sense volumetric flow or mass flow. Unlike the magnetic flowmeter, which integrates over the entire pipe cross-section, the ultrasonic flowmeter integrates along a line, so that an in-place calibration is required in many situations. Traditionally, ultrasonic flowmeters have been limited by the solids concentration in a stream — the beam is attenuated too much by the solid particles. Another traditional problem has been buildup of material on the sensor surfaces. The latter problem has been largely eliminated through development of "clamp-on" instruments which are totally non-intrinsive and require no facility modifications. Some of the more recently developed instruments have also demonstrated capabilities to make measurements in streams with 50% or more solids content, which is typical for coal slurries. These recent developments have made ultrasonic flowmeters much more viable instruments for slurry flow measurement.

2.2.2.1.3 Nuclear Magnetic Resonance Meter (Ref. 26,33)

A brief description will be given here of this instrument. More detail can be found in Reference 9. The device is currently being offered only for one inch diameter lines.

This technique requires that a major stream constituent be an element (in either elemental or molecular form) with a nucleus having a magnetic moment. Hydrogen is such an element, so the concept will apply to coal/water slurries. The meter is shown schematically in Figure 17, adapted from Reference 9. The apparatus consists of two magnets, a modulator, resonator, detector, and electronics circuitry. The first magnet (usually permanent) creates a nuclear magnetization in the hydrogen atoms, producing a spin alignment. The slurry then passes into the field of the second magnet, where a modulated signal is induced. This causes precession of the nuclear magnetic dipoles in the flow. The receiver then picks up a signal which is different in phase from the modulating signal. By virtue of a control look, the phase difference is held at a specified constant value by adjusting the frequency of the modulating signal. This ultimately results in sensing of the flow velocity as

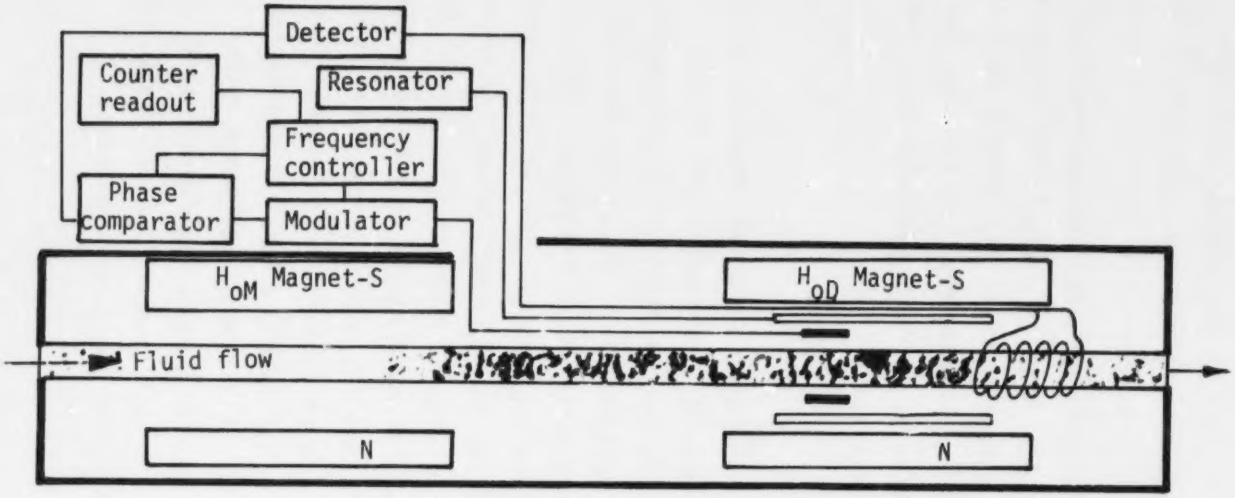
$$\bar{u} = \frac{\ell}{\phi} \omega \tag{35}$$

where

ℓ = distance between centers of modulating and receiving coils, m

ϕ = phase difference between modulator and receiver signal, radians

ω = modulator frequency, s^{-1}


Detector
Counter readout
Resonator
Frequency controller
Phase comparator
Modulator
H_{oM} Magnet-S
H_{oD} Magnet-S
Fluid flow
N
N

SEE TEXT FOR EXPLANATION

Figure 17. Schematic of NMR flowmeter, taken from Reference 33

Thus the output of the device is proportional to the average flow velocity, so that the NMR meter is identical in this respect to the magnetic flowmeter. One additional comment should perhaps be made explicit here — the term "nuclear" in nuclear magnetic resonance is used because it is the atomic nucleus which is magnetized as part of the sensing technique; however, no nuclear reactions or radioctive substances are part of the concept.

The main problem with commercialization of NMR has apparently been cost — its accuracy capabilities appear to be on a level with those of electromagnetic flowmeters. There appear to be no limitations on solid content, as there are for the ultrasonic flowmeters. In summary, the concept is valid, but at present there is hardware available only for very small (1 inch diameter or less) line sizes.

2.2.2.2 Intrusive Flowmeters

Most liquid flow measurement techniques are of an intrusive nature. These include orifices, nozzles, venturis, turbine, target meters, vortex shedding meter, etc. Any of these can be adapted with varying degrees of success to coal/water slurry flow measurements. The extent to which intrusive techniques are tried is often a function of two things: the amount of pressure put on an instrumentation engineer to cover up with something that works, usually on a very small hardware budget, and/or the enthusiasm and salesmanship of an instrument manufacturer's marketing group. Our feeling is that the intrusive flowmeter most likely to succeed in coal/water slurry applications are the vortex shedding meter, target meter, and venturi meter. Abrasive degradation would be of concern for all three; in addition, there is concern about clogging of the pressure lines in the venturi meter. The only major reason we can see for selecting any of these rather than an electromagnetic flowmeter for service in a dense coal/water slurry line would be a lower purchase price. Initial hardware savings may be offset, however, by higher maintenance costs for the intrusive device.

2.2.2.2.1 Vortex Shedding Meter

The vortex shedding meter is a relative newcomer in the flow measurement field, but has reached a high state of development in a short period of time. It is based on a simple, reliable fluid mechanics phenomenon.

When a cylinder with a cross sectional height to width ratio not much greater than unity (e.g., circular or square cross section) is aligned normal to a flowing stream, vortices will be shed periodically from either side of the cylinder as indicated in Figure 18, so long as the Reynolds number based on the cylinder height is high enough. For sufficiently high Reynolds number, the shedding fequency becomes indicpendent of the Reynolds number and the following relation is attained:

$$f = k \frac{u}{d} \tag{36}$$

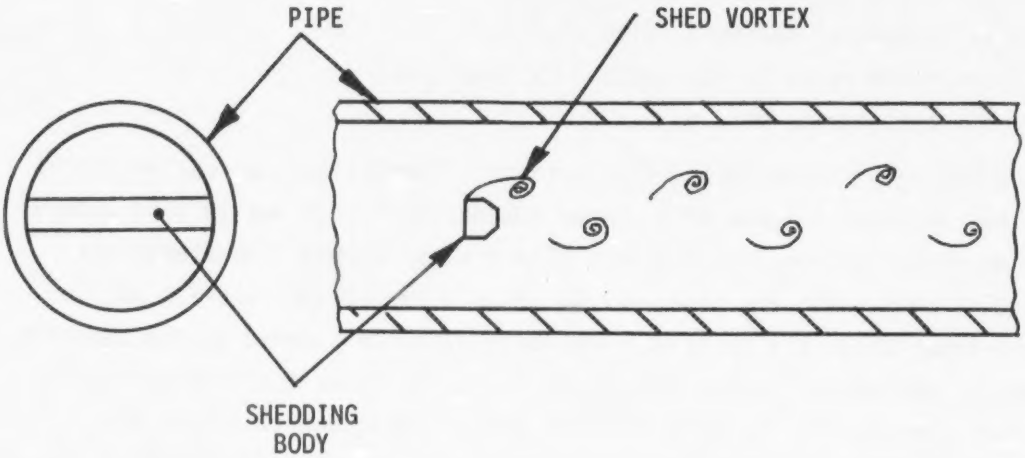
where

f = shedding frequency, s^{-1}
k = numerical constant, dimensionless
u = fluid velocity approaching cylinder, m/s
d = cylinder height, m

The shedding produces substantial pressure fluctuations, as was evidenced by the complete collapse of a large suspension bridge due to wind induced vortex shedding from the structure. In process stream flowmeters, the shedding body spans the pipe, except in very large pipes where a smaller point-type sensor may be used. The solid blockage imposed by the shedding body is substantial, about 40%, to minimize nonlinearities due to changes in the velocity profile with pipe Reynolds number, and to insure that vortices of only one frequency are shed at any one time (too great a change in velocity along the length of the shedding body would result in multiple "cells" of vortices at different shedding frequencies).

In recent years, a number of novel ways of detecting the shedding frequency have appeared. The ones most applicable to slurry flows are thermal and solid state pressure detection methods which involve no moving parts or flow through small passages.

Typical accuracy capability is ± 0.5% of reading above a known minimum flow for a given pipe size. Erosion of the sensing mechanism at the flow interface and, to a lesser extent, erosion of the shedding body itself, are the main concerns in slurry applications. Also, there would be a lower maximum allowable particle size for the vortex shedding meter than for a non-intrusive device.


PIPE
SHED VORTEX
SHEDDING BODY

VORTICES ARE SHED ALTERNATELY FROM EACH SIDE OF THE SHEDDING BODY. PRESSURE FLUCTUATIONS CAUSED BY THE SHEDDING CAN BE SENSED BY FORCE MEASUREMENT, THERMAL, OR ACOUSTIC MEANS. SHEDDING FREQUENCY IS A FUNCTION OF FLOW VELOCITY.

Figure 18. Schematic of vortex shedding meter

2.2.2.2.2 Target Meter

The target meter, shown in Figure 19, is a force measuring device. A drag body is placed in the atream at the end of a lever arm. The sensor output is a torque usually monitored by means of a strain gage bridge. The operable relation is

$$T = \ell D = \ell k \; C_D \frac{1}{2} \rho \; \overline{u^2} \; A \tag{37}$$

where

T = sensed torque, N·m
ℓ = leverl arm length, m
D = drag force on body and exposed arm, N
k = calibration factor (function of blockage), dimensionless
C_D = body drag coefficient, dimensionless
ρ = stream density, kg/m^3
A = drag body frontal area, m^2

It may be noted that, unlike the other sensors thus far considered, the target meter is not a velocity measurement device — its dependence on density puts it more in the mass flow measurement category.

The drag meter is typically capable of 1% of reading accuracy if a large enough drag body is used. Its only major deficiency in the present application is erosion of the drag body with time.

2.2.2.2.3 Venturi Meter

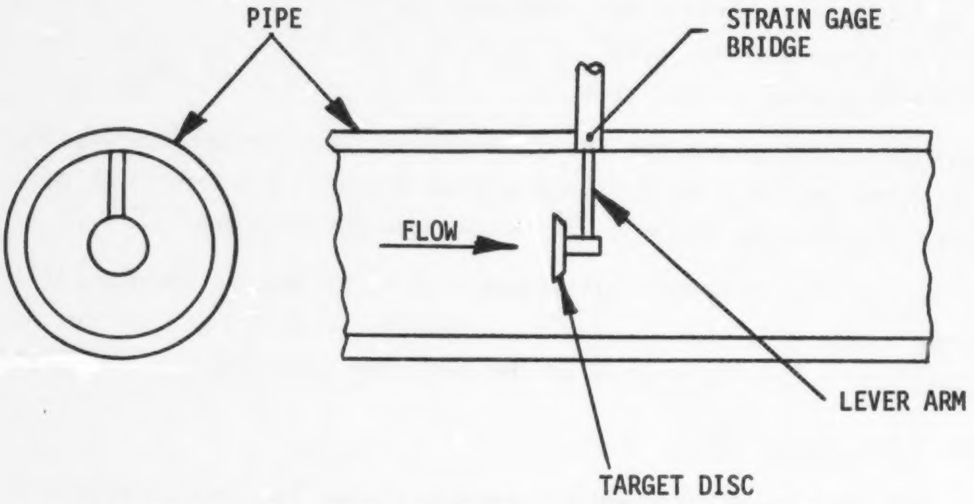
This well known differential pressure device is shown in Figure 20. It operates on the following basis:

$$\Delta p = p_e - p_e = k \frac{1}{2} \rho \; \overline{u}^2 \tag{38}$$

where

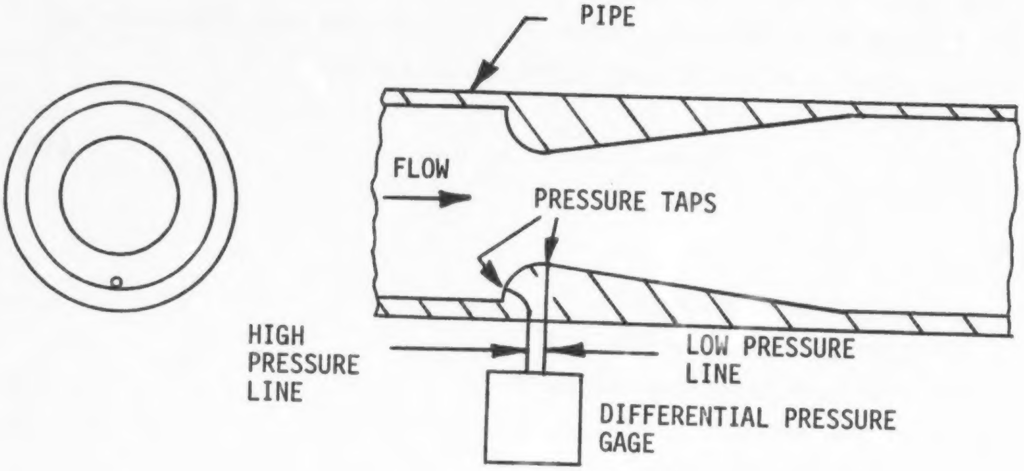
Δp = sensed differential pressure, pascals
p_e = static pressure at exit (or entry) plane, pascals
p_t = static pressure at throat, pascals
k = calibration factor, dimensionless

The venturi meter is preferred over the orifice meter or nozzle because it does not have recirculating regions. Accuracies to 1%


PIPE
STRAIN GAGE BRIDGE
FLOW
LEVER ARM
TARGET DISC

TARGET DISC IS DEFLECTED BY ITS DRAG IN FLOW STREAM. DRAG FORCE BECOMES A TORQUE VIA THE LEVER ARM, AND TORQUE IS SENSED BY STRAIN GAGE BRIDGE. TORQUE IS A FUNCTION OF MASS FLOW IN THE PIPE.

Figure 19. Schematic of target meter


PIPE
FLOW
PRESSURE TAPS
HIGH PRESSURE LINE
LOW PRESSURE LINE
DIFFERENTIAL PRESSURE GAGE

VENTURI GEOMETRY PRODUCES A DIFFERENTIAL PRESSURE PROPORTIONAL TO THE SQUARE OF THE AVERAGE FLOW VELOCITY

Figure 20. Schematic of venturi flowmeter

of reading or better can be attained for a sufficient investment in the pressure transducer. Clogging of the pressure taps and, to a lesser extent, erosion of the venturi itself, are the major problems to be dealt with in adapting a venturi meter to coal/water slurry applications.

2.2.2.3 Slurry Flowmeter/Density Meter Systems

As noted above, the most applicable slurry flowmeters must be used in conjunction with a density meter to determine the coal/water ratio and coal and water mass flow rates. This section presents a brief error analysis to show what coal flowrate accuracies can be achieved as a function of meter accuracy and coal content in the slurry. The results of the analysis show that even though good accuracy can be obtained by the meter, the system accuracy will not be nearly as good.

For the case where the average coal velocity in the slurry is equal to the average water velocity in the slurry, the coal mass flow rate can be derived from Equation (2) and expressed as follows:

$$\dot{m}_c = \frac{\rho_{sl} - \rho_w}{\rho_c - \rho_w} \rho_c \bar{u} A \qquad (39)$$

where

$\dot{m}_c$ = coal flow rate, kg/s
$\bar{u}$ = average flow velocity, m/s
A = pipe cross-sectional area, m^2
ρ_{sl} = slurry density, kg/m^3
ρ_w = water density, kg/m^3
ρ_c = coal density, kg/m^3

Standard error analysis techniques (Reference 34) were used to derive an error equation for $\dot{m}_c$ of the following form (assuming no error in the density of water):

$$\frac{\sigma_{\dot{m}_c}}{\dot{m}_c}^2 = \left(\frac{\sigma_{\bar{u}}}{\bar{u}}\right)^2 + \left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\rho_{sl}}{\rho_{sl}-\rho_{H_2O}}\right)^2 \left(\frac{\sigma_{\rho_{sl}}}{\rho_{sl}}\right)^2$$

$$+ \left(\frac{-\rho_{H_2O}}{\rho_c-\rho_{H_2O}}\right)^2 \left(\frac{\sigma_{\rho_c}}{\rho_c}\right)^2 \qquad (40)$$

where

σ_n = standard deviation of parameter n,
in same units as parameter n.

Equation (40) presents the system error, $\sigma_{\dot{m}_c}$, as a function of the individual error sources. Furthermore, normalizing the error terms in the form σ_n/n allows for easy computation in terms of percent errors rather than absolute ones. A main point in this analysis is that the terms $\frac{\rho_{sl}}{\rho_{sl}-\rho_{H_2O}}$ and $\frac{\rho_{H_2O}}{\rho_{sl}-\rho_{H_2O}}$ (especially the former) are greater than unity for coal/water slurries. This amplifies slurry density and coal density measurement errors. It is reasonable in terms of existing technology to say that we can achieve

$$\frac{\sigma_{\bar{u}}}{\bar{u}}^{\,2} + \frac{\sigma_A}{A}^{\,2} {}^{\frac{1}{2}} = .01$$

It is reasonable to take

$$\rho_{H_2O} = 1.000 \text{ g/cm}^3$$

$$\rho_c \approx 1.35 \text{ g/cm}^3$$

$$1 \leq \rho_{sl} \leq \rho_c$$

These numbers were substituted into Equation (40), using a range of values for ρ_{sl}, and $\sigma_{\dot{m}_c}/\dot{m}_c$ was calculated for

$$\frac{\sigma_{\rho_{sl}}}{\rho_{sl}}, \frac{\sigma_{\rho_c}}{\rho_c} = .001, .01, .02, .05$$

Results shown in Figure 21 as a function of percent coal by volume in the slurry. As the coal content drops to zero, the error becomes infinite since the term $\frac{\rho_{sl}}{\rho_{sl}-\rho_{H_2O}}$ becomes infinite. Figure 21 illustrates that when

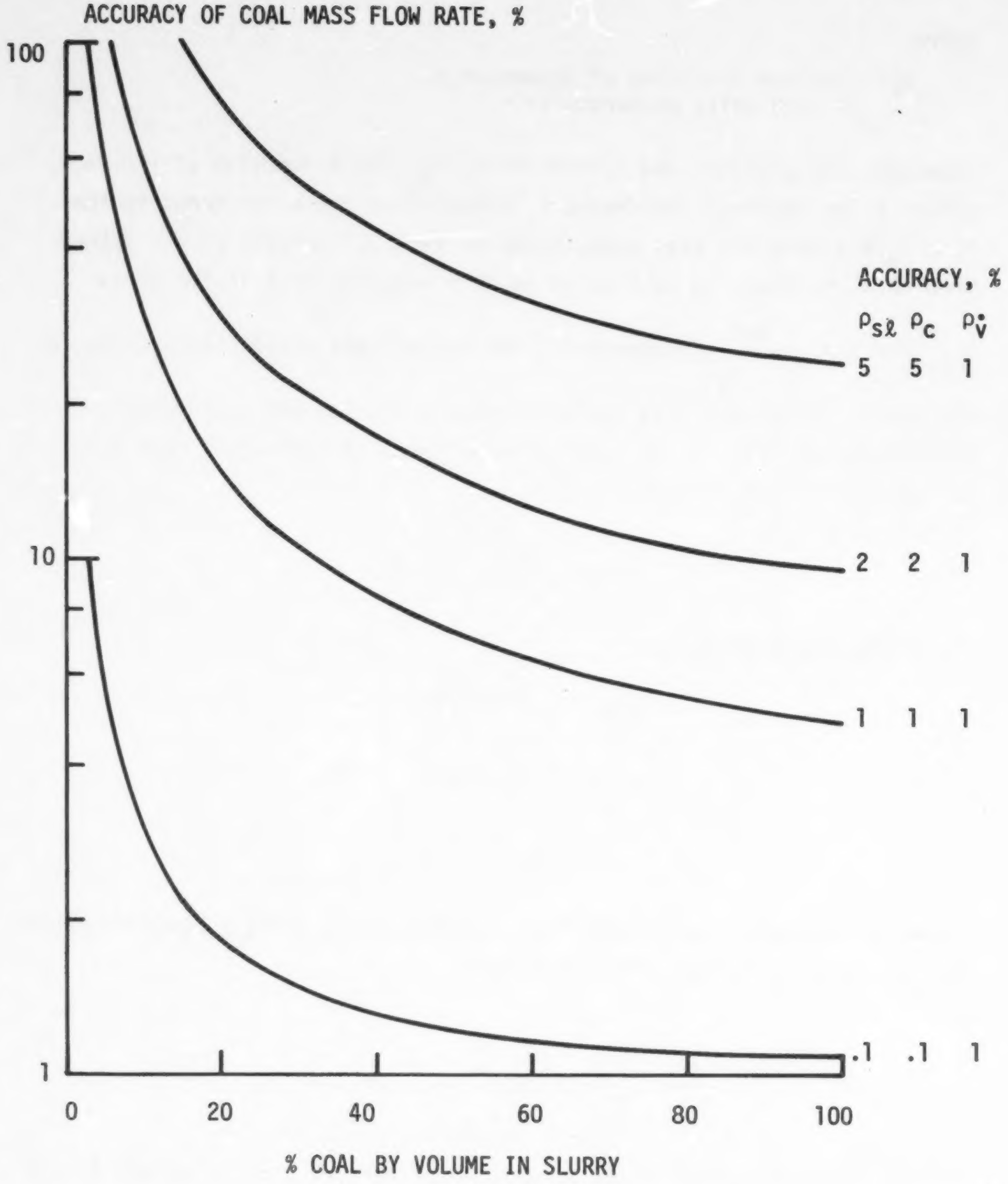


Figure 21. Accuracy of coal mass flow measurement in a coal/ water slurry for various accuracies of slurry density, coal density, and volumetric flow rate as a function of coal concentration in the slurry

individual parameters are measured to a given accuracy, say 1%, in this system, the system accuracy will be much poorer than 1%. It is clear that for this particular process measurement, a system error analysis should be rigorously carried out to determine the error in the real parameter of interest, which is the coal flow rate measurement. Such an analysis may have a strong impact on the instruments selected and on operating conditions such as slurry density.

III. HARDWARE STATUS

The previous section dealt with the physics of instrument operation. This section is concerned with the current state of development of the instruments. This ranges from readily available equipment offered in slightly varying forms by a number of manufacturers, such as weigh belt devices and electromagnetic flowmeters, to instruments such as sulfur or ash monitors which will not be commercially available for several years. The information in this section was obtained from the technical literature, vendors, users, development organizations, and regulating agencies. In the case of commonly available devices such as weigh belt instruments, we did not do an exhaustive vendor survey, but stopped after reaching the conclusion that high accuracy equipment can be obtained from a number of vendors. Where applicable, a list of vendors for a specific type of instrument is given. Such lists are acknowledged not to be all inclusive, and do not constitute recommendations for a listed vendor's product, since evaluations needed to make such a recommendation are outside the scope of the task. Vendor data should be interpreted as an indication of instrument availability and general accuracy capabilities. A list of vendors mentioned in this section and their addresses is presented at the end of the section.

3.1 COAL ANALYSIS INSTRUMENTS

3.1.1 Neutron Activation (Ref. 35-40, 10-12)

The most promising elemental analysis technique for process control is thermal neutron capture gamma ray analysis. Because the neutrons are thermal it is possible to probe a substantial volume. Furthermore, because the emitted radiation consists of fairly energetic gamma rays, the emitted signal also can propagate through substantial thicknesses of coal. Thus neutron activation allows one to sample a large volume of material simultaneously.

The basic work in this area was performed by Stewart and Hall at the Morgantown Energy Research Center, and was directed toward development of a sulfur meter capable of handling a 7 to 10 ton per hour slipstream.

The pioneering efforts at MERC involved two relatively recent state of the art advances. The heart of the technique is a high flux neutron source. The availability of man-made Californium 252 which fissions spontaneously makes it practical to achieve high neutron fluxes with relative safety. Furthermore, state of the art electronics developed at MERC make it possible to analyze over 300,000 gamma rays per second thus obtaining usable statistics in time constants of order 2 minutes. The work at Morgantown was mothballed in June, 1978, due to manpower shortages and a reordering of technical priorities (as opposed to any problems with the instrument). Good results had been obtained up to the time work was stopped.

Similar instruments are presently being developed by commercial contractors. One is a sulfur and ash meter being developed for the Homer City coal cleaning plant by MDH Industries, Inc. The MDH monitor has target accuracies of .05% for sulfur and .25% ash. As in the MERC device, a californium source is used for neutron production. The unit is to be delivered at the end of 1979, and will process approximately 100 TPH of cleaned coal. Unit costs for instruments in the near future will be about $150,000 to $200,000, and expected costs for diverting a slipstream to the instrument from a given process line, and then returning it, are $100,000 to $500,000. The device will weigh approximately two to three tons, with the bulk of that being shielding fo the radioactive source. MDH is accepting orders for the device at this time.

The most advanced system under current development is the continuous Nuclear Analyzer of Coal (CONAC) system devised by Science Applications, Inc. (SAI), in Palo Alto, California. As shown schematically in Figure 22, CONAC is a complete coal handling and analysis system consisting of a belt for flow control, a nuclear weigh scale for total mass measurement, and a neutron activation device for composition measurement. The detection scheme allows for measurement of all the elements listed in Table 8. Oxygen is determined by the difference between total mass as measured by the nuclear scale and the total mass of the other designated elements. Since the meter cannot distinguish chemical forms, a separate measurement of moisture is used. Electromagnetic or nuclear magnetic resonance approaches are the present leading candidates for the moisture measurement. The CONAC approach as it is being presently pursued seems to work best with about a 30 cm thickness of coal on the belt. This will allow for monitoring

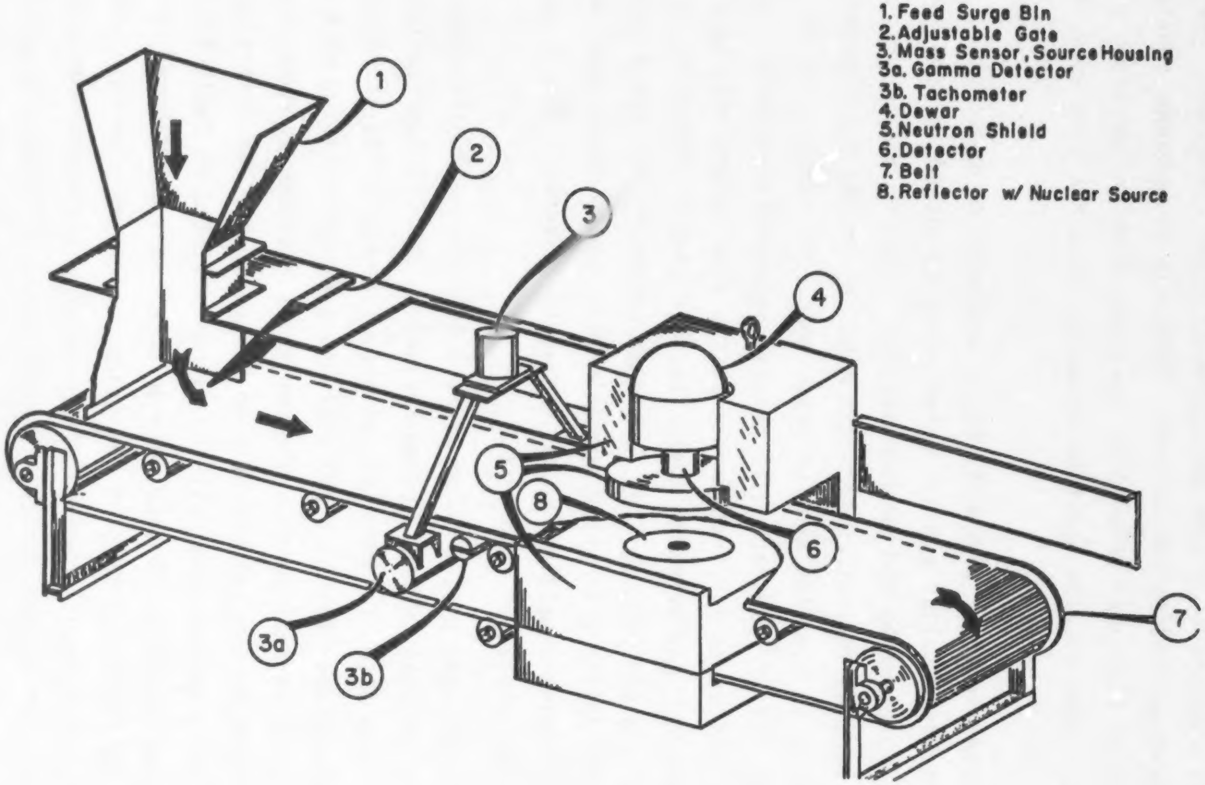

1. Feed Surge Bin
2. Adjustable Gate
3. Mass Sensor, Source Housing
3a. Gamma Detector
3b. Tachometer
4. Dewar
5. Neutron Shield
6. Detector
7. Belt
8. Reflector w/ Nuclear Source
1
2
3
4
5
6
7
8
3a
3b

Figure 22. Conceptual design of Continuous Nuclear Analyzer of Coal (CONAC) system including a nuclear scale (Ref. 39)

Table 8. COAL ELEMENTS ANALYZED BY CONAC SYSTEM AND THEIR CONCENTRATIONS IN TYPICAL COAL SAMPLES (Reference 39).

Element	Concentration, %	
	Pittsburgh #8 Coal	Wyoming Coal
Carbon	72.0	58.5
Hydrogen	5.3	5.5
Sulfur	2.9	.40
Nitrogen	1.4	.90
Silicon	1.8	1.0
Aluminum	1.3	.68
Iron	1.3	.24
Titanium	.030	.030
Sodium	.026	.050
Potassium	.11	.018
Calcium	.096	1.2
Chlorine	.079	.01

of an entire coal stream in most applications, rather than just a slipstream. This is an important feature in and of itself, since it eliminates inaccuracies involved in obtaining a representative coal sample for analysis. Most of the work at SAI to date has been sponsored by the Electric Power Research Institute (EPRI). A "full-fledged" system is scheduled to be installed for EPRI at an as yet undetermined site in 1981. Under a separate program, a sulfur and hydrogen monitor is to be delivered to Detroit Edison in 1980.

3.1.2 Gamma Ray Density Gages (Ref. 13-15)

The use of gamma ray density gages is already standard practice in a variety of industries. Their most straightforward application is just as level sensors used to determine when a container is full or empty. More sophisticated applications include sensors used to determine bulk density variations and slurry sensors used to measure slurry composition.

The precise design employed is usually strongly application dependent. Typically either Cs 137 or Co 60 radioactive isotopes are used to produce the required gamma rays. Because nuclear density gages depend upon exponential attenuation, the size of the probed volume is critical. For example, for coal and 1.25 Mev gamma rays the attenuation coefficient is roughly 0.05 cm^{-1}. Thus if a 6 foot volume is to be probed the attenuation factor is equal to:

$$e^{6 \times 12 \times 2.54 \times 0.05} = e^{9} = 8 \times 10^{3}$$

Evidently because the thickness appears in the exponential a factor of two difference can be highly significant. Consider that in the above example doubling the thickness decreases the transmitter signal by a factor of 8×10^{3}. Notice that merely increasing the source size is not necessarily a viable approach to recover this loss because of the increased health hazard.

Available commercial units incorporate a number of desirable features. Among the more prominent are source decay compensation, temperature compensation and linearization circuitry. These features automatically correct for such effects as decay of the radioactive isotope source and the intrinsic non-linearity of the exponential attenuation.

Table 9 summarizes some specifications for a representative device.

It should be appreciated that the best way to calibrate such a device is in the actual application. By doing this systematic absorptions caused by pipe walls or belt thicknesses can be readily compensated for. Furthermore, irregular volume distribution effects and the presence of hydrogen atoms can also be partially compensated for in this manner.

Table 9. DENSITY GAGE DATA

Size (I.D.):	2.5 cm to > 46 cm
Nominal accuracy:	± .5% to ± 1% of range, where a nominal range might be specific gravity 1.1 to 1.3
Ambient temperature range, °C:	-30 to +60
Response time:	15-240 seconds
Nominal cost, incl. indicator:	$3600 for 5 cm-46 cm I.D.
Vendors contacted:	Texas Nuclear Division of Ramsey Engineering; Kay-Ray

3.1.3 Neutron Moisture Meter (Ref. 16-19)

Neutron moisture determination in coal has been demonstrated by work at the Bureau of Mines and commercial instruments are now available from several vendors. It should be noted however as observed earlier that so-called moisture meters are in fact indicators of hydrogen content so that the moisture determination is only as good as a priori knowledge of the hydrogen content of the coal.

A typical system is described in Table 10. This system probes for a depth of approximately 50 cm into the coke being measured for moisture content. The required high energy neutrons are produced by an Americium/Beryllium source and detected by ionization chambers. A steel backed ceramic waveplate supplied by the vendor is fitted as an integral part of the coke hopper. In order to determine water on a percentage basis the vendor also recommends the inclusion of a density gage to normalize out bulk density variations.

Table 10. MOISTURE METER DATA

Size:	Probes 50 cm radius hemisphere
Nominal Accuracy:	± 0.5% moisture when density corrections are available
Range:	0-20% moisture
Vendor Contacted:	Kay-Ray

3.1.4 Chemical Elemental Analysis Techniques (Ref. 1)

All commercial analysis techniques suffer from the necessity to obtain representative samples. For this reason our discussion of these approaches will be quite brief because they do not appear promixing in process control applications. Details of wet chemistry measurements are outside the scope of the current discussion and hence are omitted. The interested reader can find detailed discussions in Volume 26 of the ASTM Standards.

Commercial instruments which automatically perform most of the required chemistry are available. Tables 11 and 12 illustrate the characteristics of two representative instruments. The Perkin-Elmer Model 240 performs an elemental analysis by first combusting the sample and then utilizing thermal conductivity detectors in conjunction with different types of traps which selectively absorb gases. Note in particular the very small sample size and the slow response time of the instrument. The LECO sulfur analyzer also employs combustion, but infers sulfur via IR absorption of SO_2. Note its more favorable sample size and response time. However, it still requires a representative sample and thus is of limited potential utility for on-line control.

Table 11. LECO IR-33 SULFUR ANALYZER

Sample Size	0.2-0.7 g
Range	0.01 to 3% S
Accuracy	± 3% S content
Response Time	2 minutes
Vendor Contact	LECO Corporation
Cost	$17,000

Table 12. PERKIN-ELMER MODEL 240 ELEMENTAL ANALYZER

Sample Size:	1-3 mg
Range:	C, H. N simultaneously + conversion to S
Precision:	Better than 0.3% for C, H, N or O
Response Time:	13-20 minutes
Vendor Contact:	Perkin-Elmer
Cost:	$12-20,000, dependent upon options

3.1.5 X-Ray Fluorescence (Ref. 20-24)

Both large scale and portable X-ray fluorescence spectrometers are available commercially. The primary limitations of these devices are as follows:

1. Insensitivity to low atomic number elements.
2. Small sampling volume due to attenuation by absorption.
3. Sensitivity to sample matrix composition.

Inspite of these problems X-ray fluorescence devices are currently being used in process control applications in favorable cases such as the cement industry. Furthermore, at least one company merchandises a unit especially designed to measure coal ash content.

Table 13 illustrates the features of a large spectrometer system. To achieve the stated high degree of accuracy it is necessary to have a highly homogeneous, finely ground sample. It is also necessary to provide some sort of matrix correction approach to eliminate systematic problems. Both of these features are probably incompatible with coal process control applications unless the coal is prepared in a highly homogeneous manner. Such preparation would almost certainly take too much time to serve as an on-line diagnostic.

Table 14 describes a much simpler system marketed by Texas Nuclear Corporation. This device utilizes a combination measurement of backscatter and fluorescence radiation to infer ash content. Although the backscatter radiation can penetrate a depth of order 2 cm, the fluorescence radiation has a penetration depth less than 1 mm. Thus if a matrix composition correction is necessary very fine powers are required, particularly for Ca and Ti. The device is designed for use only with pulverized coal and the quoted specifications assume that the unit is precalibrated by a sample of the type of coal to be measured. The accuracy of the measurement is considerably reduced if different types of coal are analyzed. If on the other hand uniform types of coal are analyzed, then accuracies as good as ± 0.2% ash are possible.

Table 13. X-RAY ANALYZER CHARACTERIZATION

Analyzing Range:	F to U
Nominal Accuracy:	better than 1% with suitable standard
Sample Requirements:	1-3/4" dia. by 1" thick maximum
Response Time:	typically 40 sec for 8 elements
Approximate Cost:	$100,000
Vendor Contact:	Applied Research Laboratory, Phillips Diano Corporation

Table 14. PORTABLE ELEMENTAL ANALYZER FOR ASH IN COAL

Nominal Accuracy*:	± 10% relative
Range:	5 to 25% ash
Response Time:	60 seconds
Sample Requirements:	100 mesh
Vendor Contact:	Texas Nuclear Division of Ramsey Engineering

*Specific to precalibration of a particular coal type

3.2 FLOW MEASUREMENT INSTRUMENTS

3.2.1 Dry Coal Flow

3.2.1.1 Weigh Belt Techniques

A partial list of suppliers of weigh belt equipment is given in Table 15. The size of the list indicates the easy availability of this type of equipment, as well as its widespread use. A sampling of literature from manufacturers in Table 15 was used to generate the specifications shown in Table 16. These specifications are typical of several manufacturers, although not all vendors cover the full range of belt widths. Belt scales tend to fall into one of three categories:

- High accuracy (± 0.1% to ± 0.25% F.S. accuracy) electromechanical scales
- Medium accuracy (± 0.5% to ± 1%) electromechanical scales
- Nuclear scales (± 1%)

Typical hardware costs for these three types of systems are shown in Table 17, along with a relative ranking of operating and maintenance costs. The main differences between the high and medium accuracy electromechanical scales are number and accuracy of load cells (up to four high accuracy cells for the high accuracy systems vs. one for the medium accuracy system) and number of idler rollers (usually four for the high accuracy system vs. one or two for the medium accuracy system). The nuclear scale, of course, is a totally different concept. While the two electromechanical systems are almost identical in terms of interfaces with the conveyor belt system, the nuclear scale has no physical interface except for the relatively insignificant belt speed sensor. It will generally be the case that a nuclear scale will be easiest to use, and, due to its simplicity, will tend to be preferred as long as its accuracy is compatible with system requirements. While a 1% accuracy would be acceptable for most process control requirements, it is typically not acceptable in true commerce applications where the scale is metering the coal for sales accounting. In these applications, ± 0.25% accuracy is a typical requirement.

Table 15. PARTIAL LIST OF WEIGH BELT VENDORS
(FROM REF. 50)

Type	Vendor
General	Aggregates Equipment Inc. ASEA Inc. *Auto Weigh Inc. Cardinal Scale Mfg. Co. Fairbanks Weighing Div., Colt Industries Fairfield Engineering Co. Howe Richardson Scale Co. *Inflo Resometric Scale Inc. Jeffrey Mfg. Div., Dresser Industries Inc. KHD Industrieanlagen AG, Humboldt Wedag Kilo-Wate Inc. K-Tron Corp. Lively Mfg. & Equipment Co. *Merrick Scale Manufacturing Co., Inc. *Ramsey Engineering Co. Revere Corp. of America, Sub. of Neptune Intl. Corp. Rexnord Inc. Rexnord Inc., Process Machinery Div. *Thayer Scale Hyer Industries Thurman Scale Co., Div. Thurman Mfg. Co. Webb Jarvis B., Co. Wilson, R. M., Co.
Nuclear	*Kay-Ray Inc. *Ohmart Corp. *Ramsey Engineering Co.

*literature received and evaluated.

See Table 26 for addresses

Table 16. TYPICAL WEIGH BELT SPECIFICATIONS

	Mechanical or Electromechanical		Nuclear
	High Accuracy	Medium Accuracy	
Belt Width	30 cm - 300 cm		
Turndown*	≥ 3/1		
Accuracy, % reading	± .1 - 2.5	± .5 - 1	-
% F.S.	-	-	± 1
Ambient Temperature Range, °C	≤ 0 to ≥ 40		

Table 17. TYPICAL WEIGH BELT HARDWARE COSTS

Type	Cost for 1000 ton/hour capacity unit
Electromechanical	
High Accuracy	$10,000
Medium Accuracy	$ 5,000
Nuclear	$ 6,000

Installation Costs:

High Accuracy - Highest
Medium Accuracy - Next Highest
Nuclear - Lowest

Weigh scales are sensors which are often used in control systems. A detailed discussion of control systems is beyond the scope of this report, but a few comments are in order here. The basic function of the system will be to provide specified flow rates of coal as a function of time. As noted in Section 2.2, there are two basic ways of adjusting the flow rate in a conveyor belt system – belt speed and belt loading. As is emphasized in the Appendix, optimum weigh scale accuracy is achieved for a constant belt loading, preferably about 80% of capacity. Also, system time response is minimized, especially for long belts, when the belt speed is the primary variable. Thus a system with variable belt speed and constant loading is preferable from several standpoints. A variety of control systems is discussed in References 26, 41, and 42. Both single belt systems and multiple belt blending systems are discussed. General discussions of belt scales and comments on their usage in specific situations are given in References 43-49.

The widespread use of belt scales for commerce has (surprise!) led to widespread regulatory agencies' monitoring of their use. We have been in contact with the Southern Weighing and Inspection Bureau, an acknowledged expert agency in this area, regarding procedures for calibration and use of weighing scales. These procedures are presented in annotated form in the Appendix . The procedures show that, in comparison with other process instruments of comparable accuracy, weigh scales require little attention and calibration when properly used.

The conclusions on weigh belt devices, in the context of this report, are as follows:

- Weigh scales are simple, reliable, accurate, and not notably expensive.
- Nuclear scales are easiest to install and use, and will probably be least expensive over a period of years. They are not however, as accurate as the best electromechanical scales.
- In a system involving analysis intruments to obtain constituent (e.g., carbon, sulfur, ash) flow rates, the total flow error from a weigh scale will have a negligible effect on system error.

3.2.1.2 Miscellaneous Techniques

Due to the wide applicability and availability of weigh belt devices, we did not spend a great deal of time investigating availability of other dry coal flow devices. Two devices are briefly noted here, and both are metering devices with sufficient stability and repeatability to serve as measuring devices as well.

The first is a line of screw feeders offered by Vibra Screw Incorporated. These devices operate as discussed in Section 2.2.1.2. Capacities range from about 0.05 to about 2,000 tons per hour. These devices have claimed accuracies of 1%-2% of reading. On another project, we have recently calibrated a small veeder manufactured by K-Tron, and found a repeatability of about ± 5% of reading. At first glance, the K-Tron feeder tested appeared to have a design which would lead to similar, if not better, performance than the Vibra Screw feeders. It is quite possible that increased physical size may lead to higher accuracy. These feeders are designed to attach directly to the outlet of a storage hopper. To the best of our knowledge, K-Tron feeders are only manufactured for relatively low feed rates, and cannot cover the range Vibra Screw does.

The second device is the Merrick Scale Manufacturing Company "Flow Star" feeder, which also operates at the outlet of a hopper. Maximum flow rate is about 25 tons per hour. The device may be described as a "metering turbine" feeder (as opposed to a passive sensing turbine) in which a rotating blade causes material to be removed from the bottom of the bin.

Both devices are volumetric feeders which would require recalibration in the event of coal density or particle size distribution changes. Neither would be as accurate as a good weigh belt system.

3.2.2 Coal/Water Slurries

3.2.2.1 Obstructionless Flowmeters

3.2.2.1.1 Magnetic Flowmeter

A list of magnetic flowmeter manufacturers is given in Table 18. The magnetic flowmeter is not as widely used in the coal industry as are weigh

Table 18. MAGNETIC FLOW METER VENDORS

*Brooks Instrument
Fielding Crossman & Assoc., Ltd.
*Fischer & Porter Co.
Foxboro Co.
Hoke Controls Ltd.
*Honeywell Int.
Kent Cambridge Ltd.
Ontor Ltd.
Taylor Instrument
*Warren Automatic Tool Co.

*literature received and evaluated
see Table 26 for addresses

belt devices, but demand for the instruments has led to a rather sophisticated state of development. Typical instrument specifications are listed in Table 19. These do not vary a great deal from vendor to vendor. Materials of construction are listed in Table 20, and can be supplied by a majority of vendors. For typical coal/water applications, meter dimensions are given in Table 21, along with unit costs which basically vary linearly with pipe size for pipes over 20 cm (8 in.) diameter.

A typical magnetic flowmeter system consists of three components - the sensing unit, a signal converter, and a recorder and/or controller. It is generally not a problem to locate the converter up to hundreds of meters from the sensing units. A typical magnetic flowmeter for coal/water slurry applications would have the following characteristics:

- Pipe size: $\leq$ 46 cm (18 in.) diameter
- Maximum sensor dimensions: 60-cm long x 75 cm x 75 cm
- Minimum sensor dimensions (up to 2.5-cm diameter pipe):
  35-cm long x 25 cm x 35 cm
- Materials (see Table 20)

  Body: 304 Stainless Steel

  Wetted surfaces: Liner - Rubber or Teflon
  Electrodes - 316 Stainless Steel or a more exotic material in unusual applications
- Maximum flow velocity: 9 m/s (30 ft/s)
- Preferred maximum velocity to minimize abrasion: 2 m/s (6 ft/s)
- Calibration: Sensor unit and signal converter are calibrated independently. Converter calibration devices are available. The sensor must be calibrated with actual flow, preferably using typical slurry composition dumping into volumetric tank of adequate accuracy.
- Achievable accuracy: ± 0.5% full scale or ± 1% of reading over 10-to-1 range.
- Power usage: 30-200 watts depending on size.
- Optional ultrasonic electrode cleaner to avoid buildup of sludge or grease on electrodes.

Table 19. TYPICAL MAGNETIC FLOWMETER SPECIFICATIONS

Size (I.D.)	.25 cm - 120 cm
Accuracy	
% Reading	± 1, over 10/1 range
% F.S.	± .5
Power Required	∿ 30 watts for .25 cm I.D. ∿ 100 watts for 15 cm I.D. ∿ 200 watts for 46 cm I.D.
Max Temperature, °C	65 (polyurethane lines) 150 (teflon lines)
Max Velocity, m/s	9
Min Velocity, m/s	.6

Table 20. COMMON MAGNETIC FLOWMETER LINER AND ELECTRODE MATERIALS

Liner	Electrode
Teflon	Stainless Steel, 304 or 316
Polyurethane	Hastelloy
Ceramic	Platinum
Fiberglas	Tantalum
Neoprene	Titanium
Misc. rubber compounds	

Table 21. TYPICAL MAGNETIC FLOWMETER DIMENSIONS AND COSTS

Pipe	Size	Dimensions			Cost*
cm	in	L,cm	W,cm	H,cm	
5.1	2	39	30	34	$3500
10.2	4	42	42	46	$3800
20.3	8	44	42	46	$4500
46	18	67	68	72	$12,000

*includes meter, converter, and recorder

In some literature reports, such as Reference 51, performance criticisms are lodged against the magnetic flowmeter. As the same reference shows, the bulk of these ojbections (e.g. "the pipe is not always full"; "the meter body is poorly grounded") are a result of poor communication between vendor and user or inattention to detail on the part of the user. It is our conclusion from reviewing both the literature and vendor data that problems which would be applicable to coal/water slurries have been properly addressed and overcome. A potential user should be able to purchase an adequate device, as long as stated accuracies are acceptable, from one of a number of different vendors. One item to keep in mind when purchasing a magnetic flowmeter is that there is a preferred flow velocity range for the device, which may result in selection of a meter with a different I.D. than that of the pipe to which it will be attached. If a smaller size can be selected, a cost savings will be realized.

For coal/water slurry applications, it will be the case that use of a magnetic flowmeter will probably result in lower operating/maintenance costs than will the use of any other flow device of comparable accuracy, due to the relatively noncritical wetted pieces and the obstructionless nature of the device. It is the approach which we most strongly recommend for slurry flow measurements. It must, of course, always be recognized that the magnetic flowmeter inherently measures an average flow velocity of the material passing through it, so additional diagnostic instrumentation, usually in the form of a density gage, will be required to determine the mass flow of coal in a coal/water slurry.

3.2.2.1.2 Ultrasonic Flowmeters

The "traditional" ultrasonic flowmeter shown in Figure 16 works best in a homogeneous, particle free stream. When the solid loading becomes high, the particles scatter and attenuate the pressure signals. As the loading increases, eventually a point is reached such that the signal is lost and the device will not work. A representative of the Badger Meter Manufacturing Company related during a telephone conversation that the upper limit they have found on solids content for their instrument is 25%. This is well below a typical coal slurry solids content of about 48%.

The other important limitation on traditional ultrasonic flowmeters is that they are line averaging devices which take readings along a pipe diameter. This average velocity must be related analytically, or preferably, empirically, to the average flow velocity. If the relationships between the two changes, as it almost always will, as a function of flowrate and/or solids content, then the output will be nonlinear with flowrate and extensive clibration will be required. This is in contrast to the more linear magnetic flowmeter which would generally require only a single point calibration.

Presently available ultrasonic flowmeters are of two types, as distinguished by the transducer/fluid interface. The more "traditional" instruments have the transmitters and receivers in direct contact with the fluid, while the "clamp-on" devices, so-called because they can be clamped onto an existing pipe, send and receive signals through the pipe wall. To obtain parallel faces between the transmitter and receiver, recesses in the pipe wall are used (always in the case of wetted transducers and sometimes in the case of clamp-on transducers) Clamp-on transducers are especially attractive, as long as accuracy can be maintained, since they require no modifications to the flow line for installation or removal. They also eliminate the problem of coating of the sensors which often occurs in the case of wetted sensors.

Two relatively new clamp-on flowmeters appear capable of handling the heavy solids loading found in coal slurries. One is a system which transmits a signal in one direction across the pipe, and is manufactured by Controlotron Corporation. In appearance it is similar to the device offered by Badger, but has been found to be acceptable in slurry lines with up to at least 50% solids content. The other is a device manufactured by Polysonics, and makes use of a single transducer clamped to one side of a pipe. In a coal slurry application, the transmitted signal would be reflected off the coal particles and back to the sensor. The particle velocity is then determined by a Doppler shift. This instrument has also been found acceptable for use in dense slurries. It will work best when the flow field is uniform with the particles moving at the fluid velocity. Since these conditions are not present in real life, in-place calibration as a function of flow rate, particle size, and solids loading should be performed for optimum accuracy.

Nominal manufacturer specifications are shown in Table 22, along with representative costs. It is usually the case that clamp-on devices will be preferred, since they are less expensive and require minimum modifications to an existing piping system. Clamp-on transducers perform best on a steel pipe, which is what would commonly be used in coal/water slurry systems. For larger pipe sizes, 30 cm (12 in.) or greater, the ultrasonic flowmeter will tend to be less expensive than the magnetic flowmeter in terms of purchase price and installation cost. The newer ultrasonic flowmeters have not been available long enough to permit long term comparisons with magnetic flowmeters. They may eventually prove to be at least as acceptable as magnetic flowmeters.

3.2.2.1.3 Nuclear Magnetic Resonance Meter

The Badger Meter Manufacturing Company holds the patent on the Nuclear Magnetic Resonances flow meter. At present, the largest pipe size for which they offer a device is 2.5 cm (1 in.). There are at present hardware difficulties relating to the size of magnet coils which make larger sizes impractical. The listed accuracy of the device is 1% of reading, and a typical system with accessories costs about $5500. Due to the size limitation, this device in its current state of development is not applicable to coal/water slurry measurements.

3.2.2.2 Intrusive Flowmeters

The survey-type articles reviewed (References 26, 29, 51 and 52) are unanimous in not recommending intrusive flowmeters for this type of application. The devices considered below are generally less expensive to purchase than magnetic flowmeters, but it is likely that the purchase price savings would be more than offset by maintenance costs. In addition, there is greater probability of data loss due to instrument failure as well as the threat of possible line blockage or erratic flow due to the presence of the meter in the stream. We recommend that intrusive devices by considered for coal/water slurries only in the event that obstructionless devices such as the magnetic flowmeter are clearly unacceptable for some reason. Presented below are discussions of various devices in order of our estimation of their probable success.

Table 22. ULTRASONIC FLOWMETER DATA

Size (I.D.)	2.5 cm - 50 cm
Accuracy	
% Reading	± 1 above 30 cm/s (±.1 for special order equipment)*
Temperature Range, °C	∿ 0 to 50
Nominal system cost	\$2000-\$6000 for 15 cm - 50 cm pipes
Vendors contacted	Badger Meter Mfg. Co. Controlotron Corp. Panametrics Polysonics

*Panametrics offers custom systems in this range but has not worked with coal/water slurries.

See Table 26 for vendor addresses.

3.2.2.2.1 Target Meter

The blockage of this type of device is primarily in the center of the pipe (Figure 19) rather than at the walls, so accumulation problems would be minimized. There are three main potential problems with use of target flowmeters in coal/water slurries in addition to the problem of possible pipe clogging. These are:

- Loss of accuracy due to abrasion of the drag body.
- Mechanical deformation due to large particle impact.
- Clogging of flowmeter components such as the overrange mechanism.

Abrasion will change the drag characteristics, as would any deformation. The drag body would need periodic replacement, which will show up as a labor cost and a minor hardware cost. A typical overrange mechanism is shown in Figure 23, and is a device to prevent damage to the strain gage bridge/lever assembly. Coal particles could lodge in this mechanism and render the instrument useless. Removing the overrange mechanism leaves the instrument more susceptible to major damage.

Nominal cost and specification data are listed in Table 23. Target meters work well in clean liquid streams and in clean or dirty gas streams. Our own evaluation in a gas stream on another EPA program (Reference 51) confirms a 1% accuracy capability. There are no truly fundamental reasons why the target meter cannot be used in slurry lines, but they have yet to be recommended, especially for dense slurries, by unbiased sources.

3.2.2.2.2 Vortex Shedding Meter

Potential problems with this approach are possible accumulation of coal near the relatively large shedding body, leading to inaccuracies, and abrasion of the shedding body, in addition to possible pipe clogging. As in the case of the target meter, the intrusive body would require periodic replacement.

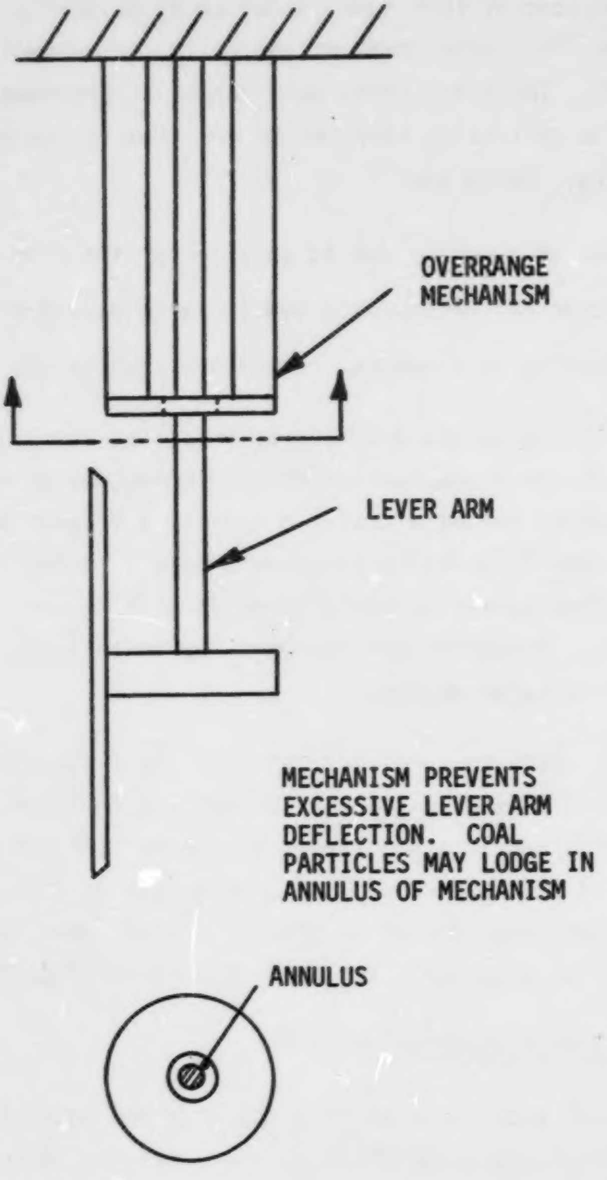

OVERRANGE MECHANISM
LEVER ARM
MECHANISM PREVENTS EXCESSIVE LEVER ARM DEFLECTION. COAL PARTICLES MAY LODGE IN ANNULUS OF MECHANISM
ANNULUS

Figure 23. Detail of overrange mechanism for target meter

Table 23. TARGET METER DATA

Size (I.D.)	1.9 cm to > 50 cm
Accuracy	
% Reading	± .5 to 2 over 10/1 range
Power required	of order 10 watts
Max Temperature, °C	177
	400 (optional)
Max Flow Velocity, m/s	∿ 4.5
Min Flow Velocity, m/s	∿ .1
Approximate system cost, including indicator	∿ $2700 for 30 cm dia
Vendors contacted	Ramapo Instrument Co.
	Engineering Measurement Co.

See Table 26 for vendor addresses.

Costs and specifications are shown in Table 24. In their current state of development, vortex shedding meters are reliable and accurate in clean flows, but there is insufficient data available to determine their capabilities in dense slurries.

3.2.2.2.3 Venturi Meters

Some manufacturers of venturi meters do not recommend their use for anything worse than "reasonably clean liquid" applications, while others are more adventurous and feel they can handle slurry flows. Venturi meters have a better probability of success than orifice plates or nozzles because they do not cause recirculating regions to be set up. The overriding concern about use of a venturi meter, of course, will be clogging of the relatively small pressure taps. This would require use of an automatic purge system to maintain clear lines. The duty cycle of the purge system would likely have to be high (20% or more) so that truly continuous measurement would not be obtained. Some users have obtained good results with an added purge system.

Costs and specifications for typical venturi meter installations are shown in Table 25. A purge system would be an additional cost item, and would be the key to a successful system. Since most manufacturers do not generally recommend venturi meters for this type of application, great care must be taken if this approach is selected.

3.2.2.3 Density Gages

Two types of density gages are in common use in slurry flow systems - nuclear (gamma ray) gages, as discussed in Section 3.1, and ultrasonic gages. An ultrasonic gage is shown schematically in Figure 24. Like the ultrasonic flowmeter, it has a transmitter and receiver of high frequency pulses. Received signal strength is the measured variable, and is inversely proportional to the solids content in the stream. Eventually a point is reached where signal attenuation is too great and no usable signal is received. This upper limit is a function of both solids content and pipe diameter.

Table 24. VORTEX METER DATA

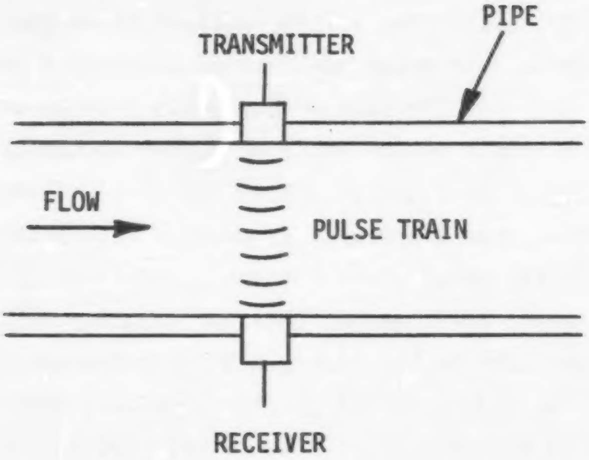
Size (I.D.)	2.5 cm to 274 cm
Accuracy, % Reading	± .25 to ± 1 (10/1 range)
Max Temperature, °C	120
Min. Flow Requirement	Pipe Reynolds number ≥ 10,000
Approximate System Cost, including Indicator	\$4700 (5 cm I.D.) \$5700 (10 cm I.D.) \$6600 (20 cm I.D.) \$13,000 (46 cm I.D.)
Vendor Contacted	Neptune/Eastech

See Table 26 for vendor addresses.

Table 25. VENTURI METER DATA

Size (I.D.)	.6 cm to 150 cm
Accuracy of Δp Measurement, % F.S.	± .25
Approximate system Cost, including Indicator but not Purge System	\$2000 (10 cm I.D.) \$2200 (20 cm I.D.) \$3200 (46 cm I.D.)
Vendors Contacted	Fischer & Porter Flow-Dyne Engineering

See Table 26 for vendor addresses.


PIPE
TRANSMITTER
FLOW
PULSE TRAIN
RECEIVER

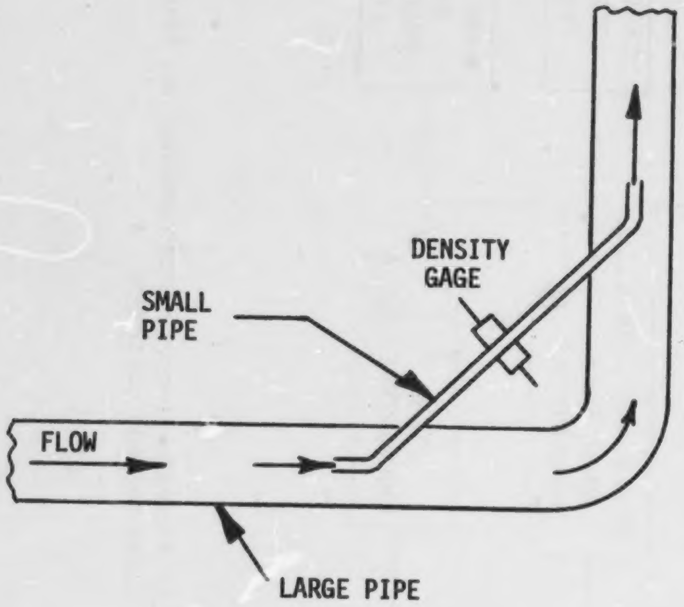
STRENGTH OF RECEIVED SIGNAL FOR PURE LIQUID ESTABLISHES REFERENCE. SIGNAL IS ATTENUATED BY SOLID PARTICLES IN FLOWING (OR STATIC) STREAM. CALIBRATION ESTABLISHES RELATION BETWEEN % SOLIDS AND SIGNAL STRENGTH.

Figure 24. Ultrasonic density gage

For the device manufactured by National Sonics, the product of solids content in percent (by volume) and pipe I.D. in inches must be less than or equal to 60. This means that the dense coal/water slurries typically encountered would limit pipe size to 2.5-5 cm (1-2 inches), meaning that the device would be applicable primarily in situations as depicted in Figure 25, where a small diameter slipstream is taken from the main line and the sensor mounted on the small slipstream line. Such a configuration would have to be carefully designed to avoid obtaining a non-representative sample in the slipstream. Except in the case of very dilute slurries or very small lines, the ultrasonic density gage will not be applicable to coal/water slurries.

3.2.2.4 Slurry Flowmeters/Density Gage Systems

A typical system involving use of a density gage and flowmeter is shown in Figure 26, taken from a Texas Nuclear catalogue. The example shown would be for a case where the desired parameters are mass flow rate and stream density. For the case of coal mass flow as an output, a microprocessor or other logic device would be needed to compute coal mass flow, as in Equation (39). In light of discussion above of various instruments, it is reasonable to expect a slurry volumetric flow accuracy of ± 1% of reading, and a slurry density measurement accuracy of ± .1% to ± .2% of reading. If we arbitrarily assume that the accuracy of the coal density measurement is the same as the slurry density measurement, and that the coal content of the slurry is 20% to 60% by volume, then the accuracy of the coal mass flow measurement will be between about 1.8% and 4%. This is a significantly lower accuracy than would tend to be inferred from the individual component accuracies, and clearly shows why flow rate measurements of a dry coal flow is the preferred technique when possible.


DENSITY GAGE
SMALL PIPE
FLOW
LARGE PIPE

ULTRASONIC DENSITY GAGE REQUIRES SMALL PIPE FOR DENSE SLURRY. SLIPSTREAM APPROACH PROVIDES SMALL DIAMETER, REASONABLY REPRESENTATIVE SLIPSTREAM

Figure 25. Slipstream concept for ultrasonic density gage

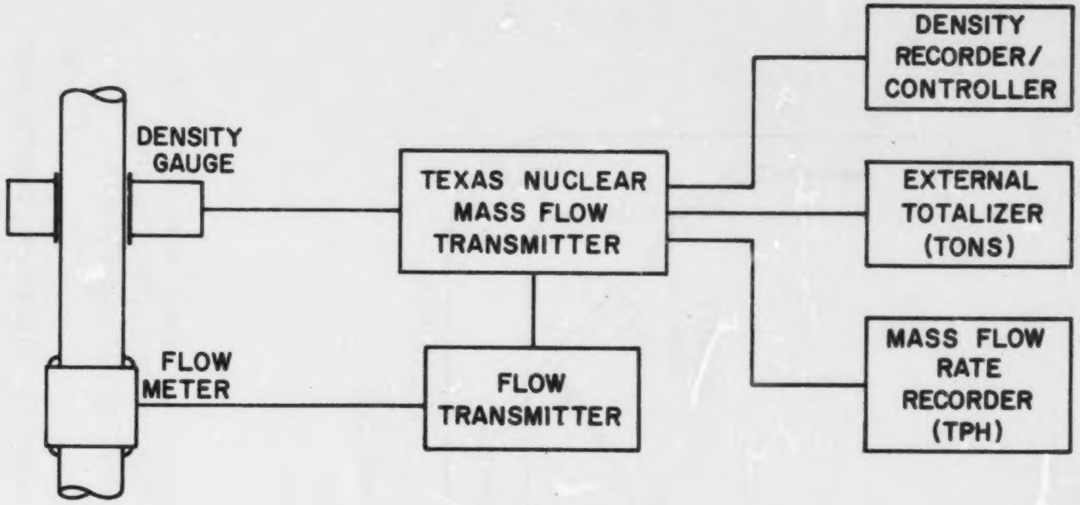

DENSITY GAUGE
FLOW METER
TEXAS NUCLEAR MASS FLOW TRANSMITTER
FLOW TRANSMITTER
DENSITY RECORDER/ CONTROLLER
EXTERNAL TOTALIZER (TONS)
MASS FLOW RATE RECORDER (TPH)

Figure 26. Typical flowmeter/density gage combination, taken from Texas Nuclear catalogue

Table 26. VENDOR ADDRESSES

Weigh Belts - General

Aggregates Equipment Inc.
9 Horseshoe Rd.
Leola, Pa 17540

ASEA Inc.
4 New King St.
White Plains, NY 10604

Auto Weigh Inc.
P.O. Box 4017
1439 N. Emerald Ave.
Modesto, Cal 95352

Cardinal Scale Mfg. Co.
203 E. Daugherty
Webb City, Mo 64870

Fairbanks Weighing Div., Colt Industries
711 E. St. Johnsbury Rd.
St. Johnsbury, Vt 05819

Fairfield Engineering Co.
324 Barnhart St.
Marion, Ohio 43302

Howe Richardson Scale Co.
680 Van Houten Ave.
Clifton, NJ 07015

Inflo Resometric Scale Inc.
2324 University Ave.
St. Paul, Minn 55114

Jeffrey Mfg. Div., Dresser Industries, Inc.
912 No. Fourth St.
Columbus, Ohio 43216

KHD Industrieanlagen AG, Humboldt Wedag
Weirsbergstrasse, D5
Koeln 91, Fed. Rup. of Germany

Kilo-Wate Inc.
Box 798
Georgetown, Tex 78626

Weigh Belts - General (Cont.)

K-Tron Corp.
P.O. Box 548
Glassboro, NJ 08028

Lively Mfg. and Equipment Co.
P.O. Box 338
Glen White, W. Va 25849

Merrick Scale Manufacturing Co., Inc.
180-192 Autumn Street
Passaic, N.J. 07055

Ramsey Engineering Co.
1853 W. County Rd. C
St. Paul, Minn 55113

Revere Corp. of America, Sub. of Neptune Intl. Corp.
North Colony Rd.
Wallingford, Conn 06492

Rexnord Inc.
P.O. Box 2022
Milwaukee, Wis 53201

Rexnord Inc., Process Machinery Div.
P.O. Box 383
Milwaukee, Wis 53201

Thayer Scale Hyer Industries
Rt. 139
Pembroke, Mass 02359

Thurman Scale Co., Div Thurman Mfg. Co.
1939 Refugee Rd.
Columbus, Ohio 43215

Jervis B. Webb Co.
9000 Alpine Ave.
Detroit, Mich 48204

R. M. Wilson Co.
Box 6274
Wheeling, W. Va 26003

Weigh Belts - Nuclear

Kay-Ray Inc.
516 W. Campus Dr.
Arlington Heights, Ill 60004

Ohmart Corp.
4241 Allendorf Drive
P.O. Box 9026
Cincinnati, Ohio 45209

Ramsey Engineering Co.
1853 W. County Rd. C
St. Paul, Minn 55113

Magnetic Flowmeters

Brooks Instrument Div., Emerson Electric Co.
Hatfield, Pa 19440

Fielding Crossman and Assoc., Ltd.
232 Yorkland Blvd.
Willowdale, Ont. Canada

Fischer and Porter Co.
Warminster, Pa 18974

Foxboro Co.
Foxboro, Mass 02035

Hoke Controls Ltd.
2240 Speers Road
Oakville, Ont., Canada

Honeywell Int.
1100 Virginia Drive
Fort Washington, Pa 19034

Kent Cambridge Ltd.
80 Doncaster Ave.
Thornhill, Ont., Canada

Ontor Ltd.
12 Leswyn Rd.
Toronto, Ont., Canada

Taylor Instrument, Process Control Div., Sybron Corp.
95 Ames St.
Rochester, NY 14601

Warren Automatic Tool Co.
P.O. Box 18345
Houston, Tex 77023

Ultrasonic Flowmeters

Badger Meter Mfg. Co., Precision Product Div.
6116 E. 15th St.
Tulsa, Okla 74115

Controlotron Corporation
155 Plant Avenue
Hauppauge, L.I., New York 11787

National Sonics
250 Marcus Boulevard
Hauppauge, New York 11787

Polysonics
3230 Mercer Street
Houston, Texas 77027

Target Meters

Engineering Measurements Company, Inc.
P.O. Box 346
1840 N. 55th St.
Boulder, Colo 80302

Ramapo Instrument Co., Inc.
2 Mars Court
P.O. Box 428
Montville, NJ 07045

Vortex Meters

Neptune/Eastech
308 Talmadge Rd.
Edison, NJ 08817

Panametrics
220-T Cresent St.
Waltham, Mass 02154

Venturi Meters

Fischer and Porter Co.
Warminster, Pa 18974

Flow-Dyne Engineering, Inc.
P.O. Box 9034
Fort Worth, Tex 76107

Density Gages

National Sonics
250 Marcus Blvd.
Hauppauge, NY 11787

Texas Nuclear
9101 Research Rd.
P.O. Box 9267
Austin, Tex 78757

(See also Kay-Ray Inc., listed in Weigh Belts-Nuclear section.)

Coal Analysis Instruments

Applied Research Laboratories
P.O. Box 129
Sunland, CA 91040

DIANO Corporation
9 Commonwealth Ave.
Woburn, Mass. 01801

LECO Corporation
3000 Lakeview Ave.
St. Joseph, Mich. 49085

MHD Industries, Inc.
426 West Duarte Road
Monrovia, CA 91016

Perkin-Elmer Corporation, Instrument Div.
Main Avenue
Norwalk, Conn. 06852

Philips Electronic Instruments, Inc.
85 McKee Drive
Mahwah, NJ 07430

Science Applications, Inc.
5 Palo Alto Square
Suite 200
Palo Alto, CA 94304

Watkins Johnson
3333 Hileview Ave.
Palo Alto, CA 94304

(See also Kay-Ray Inc., listed in Weigh Belts-Nuclear section.)

IV. TEN YEAR PROJECTION OF INSTRUMENT DEVELOPMENT AND AVAILABILITY

This section consists of a list of predictions for instrumentation improvements over the next decade. The reason for presenting these predictions is that we expect that coal analysis instruments, specifically of the neutron activation type, will become commercially available during this time period, and will potentially have a large effect on overall instrumentation and control systems.

4.1 WEIGH BELT INSTRUMENTS

Electromechanical weigh belt devices have pretty well reached their limits of accuracy, reliability, and simplicity. No significant future improvements are considered likely. Nuclear weigh scales are cost competitive with the "medium" accuracy weigh belt, but cannot meet the accuracies required by some regulatory agencies. While the nuclear scale is insensitive to belt/weighbridge interface factors which can lead to errors in electromechanical systems, it is more sensitive to coal composition variations. It appears, then, that electromechanical scales are ultimately limited by systematic errors primarily related to the belt, while the nuclear scale is limited by random errors due to coal property variations. Two basic paths are available for nuclear scale development: improvement of accuracy to become competitive with high accuracy electromechanical scales, and lowering of cost to stay financially more attractive than medium accuracy electromechanical scales. There is insufficient information at present to determine if the high accuracy goal can be achieved.

4.2 SLURRY INSTRUMENTS

At present, there is not a great demand for coal/water slurry instrumentation. If slurry pipelines become more common (the critical issue being right-of-way conflicts with railroads), demand may increase. Like weigh belt devices, the electromagnetic flowmeter has pretty well reached a maximum state of development. Recent improvements have been in the materials area, to decrease maintenance, and in installation details to try to make operation as foolproof as possible. A more widespread need for coal/water slurry flowmeters may provide incentive to manufacturers of devices other than magnetic flowmeters (particularly intrusive devices) to improve their instruments and/or adequately demonstrate that they will work well in dense slurries. In large pipes, where the cost of magnetic flowmeters is high, ultrasonic flowmeters would be significantly less expensive. It is likely that nuclear density gages will maintain their superiority in dense slurries, while ultrasonic density gages will be more accurate in very dilute slurries. New developments in slurry instrumentation would be spurred by increased demand, or by success in a similar application.

4.3 COAL ANALYSIS INSTRUMENTS

The problems associated with obtaining a representative coal sample (typically a few grams from hundreds or thousands of tons) for instruments using techniques such as X-ray fluorescence are very difficult and expensive to overcome, when they can be overcome at all. That is a major reason why techniques such as thermal neutron activation, which can look at a major portion, or even all, of the coal stream, are so attractive and hold the greatest promise for future development. The concept has been adequately demonstrated. MDH and SAI are currently working on deliverable hardware systems. The early units will concentrate on sulfur, hydrogen, and ash. Further development should lead to a system capable of monitoring all important coal constituents. As the eighties progress, the technology should expand from one of a kind devices with rather limited capabilities to general availability of complete monitoring systems, which, like the CONAC system being developed at SAI, will include total mass measurement and flow control in addition to the basic analysis instrumentation.

4.4 INTEGRATED INSTRUMENTATION SYSTEMS

The impact of increasing high accuracy instrument availability and the proliferation of low cost microprocessors is offering the possibility of a revolution in process instrumentation and control. For example, continuous knowledge of the flowrate and heating value of coal being fed to a furnace would allow for the possibility of continuous control of combustion parameters such as temperature and air/fuel ratio to optimize the combustion process. Monitoring of sulfur content of the incoming coal would allow for optimum control of a clean-up device such as a wet scrubber. It is being shown routinely that proper instrumentation pays for itself, and more, very rapidly through increased energy efficiency. With the anticipated availability of good analysis devices, the prospects for better energy utilization and optimum environmental quality control become even better.

V. SUMMARY AND CONCLUSIONS

5.1 PRINCIPLES OF INSTRUMENT OPERATION

Relevant techniques were presented in detail to give a general understanding and to give an idea of fundamental limitations. For example, a difference in ultimate utility between neutron activation devices and fluorescence radiation devices is shown by the fact that the former can operate with a penetration depth of order one meter, while the latter is limited to penetration depth of order one millimeter. This has strong implications on instrument configuration and utility.

In contrast to the rather sophisticated physics of coal analysis equipment, operation principles of most flow measurement devices are fairly simple. This simplicity has meant that flow measurement devices have been more easily developed, and have been in wide use for many years.

The material presented makes it clear that there are many techniques available for the measurements of interest. Availability of instrumentation, however, is another matter, especially in the case of coal analysis devices.

5.2 HARDWARE STATUS

Instruments available now for coal analysis, with the exception of the neutron moisture meter, are capable of analyzing only small samples, which means that a sophisticated sampling system is required. The moisture meter itself is actually a hydrogen indicator, which means that the coal hydrogen content must be known independently to determine the moisture content. It has been the observation of MERC personnel that the hydrogen content in coal is in fact constant for a given coal type. Although the MERC program has been halted, instrument development is proceeding at MDH and SAI, with delivery of the first MDH sulfur and ash monitor expected by the end of 1979. Neutron activation devices are of particular interest because they hold the promise of sampling entire coal streams, thus eliminating the major problem of obtaining a representative sample.

Weigh belt devices, either electromechanical or nuclear, and electromagnetic flowmeters (typically coupled with nuclear density gages) are the most used devices for dry coal flow measurement and coal/water slurry flow measurement, respectively, and will be acceptable for most situations. Weigh belt technology is especially highly developed, in part due to regulatory considerations. Intrusive devices may be applicable to slurry flow measurements, but this has not been clearly demonstrated as yet. Recent developments in ultrasonic flowmeters have made them much more applicable to slurry flow measurement.

5.3 EPA/IERL AND COAL MONITORING INSTRUMENTS

Weigh belt devices are sufficiently advanced, and their use in many situations sufficiently monitored by various regulatory agencies, that they should not need EPA attention. Similarly, electromagnetic flowmeters are a very standard item and do not appear to need attention, in terms of field evaluations for example, except in unusual circumstances. As far as other slurry flow measurement devices are concerned, we feel that a reasonable approach is to let vendors demonstrate that their devices are acceptable for (dense) coal/water slurries.

At such time as devices like the neutron sulfur meter become commerically available, IERL will likely wish to be involved in collaborative testing or other evaluation of the devices. This, however, will not be taking place for at least a couple of years.

Perhaps the most reasonable area for IERL investigation in the near future is instrumentation/control systems which make use of the kinds of instruments discussed in this report. The thrust of the investigation would be to determine how to make the best uses of available and soon-to-be-available instrumentation to control the operation of sources such as coal-fired utilities to minimize pollutant emissions through direct combustion control and/or optimizing operation of devices such as wet scrubbers. The greatest ultimate value of the instruments discussed herein is not just as monitoring sensors, but as components in an active control system, either on sources of direct coal combustion, or in coal cleaning plants.

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VII. GLOSSARY

SYMBOL	USAGE	DIMENSIONS
A	area	m^2
A	atomic mass	amu
B	magnetic flux density	volt-s/m^2
B	area	m^2
B_e	binding energy	erg
c	speed of sound	m/s
c	speed of light	m/s
C_D	drag coefficient	—
D	drag	N
d	pipe diameter	N
d	cylinder height	m
E	electromotive force	volt
E_o,E_1	energy	erg
f	functional relationship	—
f	frequency	s^{-1}
h	Planck's constant	erg-s
h_v	photon energy	erg
I	gamma rays/100 neutrons	—
I	intensity	photon/cm^2
K,k	constant or calibration factor	—
K_α,K_β,etc	energies	erg
KE	kinetic energy	erg
L	thickness	cm

GLOSSARY (cont.)

SYMBOL	USAGE	DIMENSIONS
ℓ	length	m
$\dot{\ell}$	belt speed	m/s
ℓ_B	belt length	m
m	mass	kg
$\dot{m}_T$	total mass flowrate	kg/s
$\dot{m}_c$	coal flow rate	kg/s
m_{i_e}	sensed mass of constituent i	kg
m_i	mass flow rate of constituent i	kg/s
m_o	electron mass	g
N	number density	scatterers/cm^3
N_e	electron number density	cm^{-3}
N_o	Avagadro's number	—
n	particle density	particles/cm^3
p_e	entry static pressure	pascals
p_t	throat static pressure	pascals
Δp	differential pressure	pascals
R	radius	cm
R	ratio	—
Re_p	pipe Reynolds number	—
S	analytical sensitivity	$\frac{\#\gamma\text{-rays-barn}}{100\ \text{neutrons}}$
S	flux	particle/cm^2
S_0, S_1	gamma ray signals	—
T	torque	N-m
t	time	s

GLOSSARY (cont.)

SYMBOL	USAGE	DIMENSIONS
t	thickness	cm
u	fluid velocity	m/s
$\bar{u}$	average velocity	m/s
V	velocity	m/s
V_e	effective sampling volume	m^3
V_s	solids volume	m^3
V_T	control volume	m^3
V_ℓ	liquid volume	m^3
$\dot{V}$	volumetric flow	m^3/s
v_m	mean velocity along pipe diameter	m/s
X	depth	cm
Z	atomic number	—
θ	angle between instrument and pipe axes	—
λ	wavelength	cm
μ	absorption coefficient	cm^{-1}
ν	frequency	hertz
ξ	logarithmic decrement of energy	—
ρ	density	kg/m^3
ρ_c	coal density	kg/m^3
ρ_ℓ	liquid density	kg/m^3
ρ_m	material density	kg/m^3
ρ_s	solid density	kg/m^3

GLOSSARY (cont.)

SYMBOL	USAGE	DIMENSIONS
ρ_{sl}	slurry density	kg/m^3
ρ_w	density of water	kg/m^3
σ	cross section	cm^2 or barn = 10^{-24}cm^2
σ	constant	—
σ_n	standard deviation of parameter n	—
ϕ	angle	—
ϕ	phase difference	—
χ_i	mass fraction of constituent i	—
ω	modulator frequency	s^{-1}

APPENDIX

PROCEDURE FOR WEIGH BELT CALIBRATION AND USE

Of the types of instrument systems considered in this report, only weigh belt systems are sufficiently advanced and identifiable as systems to warrant recommendations of operating procedures. Continuous coal analysis instrumentation is not sufficiently developed, and there are at present too few applications for coal/water slurries.

Our research has led to the conclusion that the Southern Weighing and Inspection Bureau in Atlanta, Georgia has promulgated weigh belt procedures which provide maximum accuracy with a minimum of calibration cost to the user. The Bureau has supplied us with their standard procedures. After a quick review of the received procedures, we decided that the accuracy requirements could probably be loosened a bit without adversely impacting overall system requirements in a system which included (less accurate) coal analysis instrumentation. We then proceeded to look for possible shortcuts which could save calibration time while maintaining a flow accuracy of about 1%. After a closer inspection and conversations with the Bureau, we came to the conclusion that the procedures already were designed to minimize calibration work, and that their requirements should not be relaxed. This also indicates that the required accuracy levels can be achieved by available hardware systems.

Presented below are verbatim copies of the information supplied by the Bureau. Not all items, such as requirements to supply data to the Bureau, are applicable to the present case. We have annotated on an item-by-item basis, as felt necessary, by using an encircled number to the left of the Bureau's item number, as in

① 2. All inspection requirements . . .

Our notes are presented by number after the Bureau's last report to avoid confusion. The notation primarily deals with two topics — items which are of a purely regulatory nature and directly involve the Bureau, and items would not apply if a nuclear weight detection instrument were used. Three documents are presented: "Requirements for the Approval of Belt Conveyor Scales," "An Explanation of Rules for the Inspection, Testing, and Calibration of Belt Conveyor Scales," and "Chain Test". They are presented in chronological order, and there is some redundancy. The first two reports are broad in scope and offer a wealth of user data on installation and use as well as calibration, and the second report offers a complete list of definitions of terms associated with the instruments. The third document deals solely with chain calibration checks for mechanical and electromechanical scales.

All readers of this report must keep in mind that the annotation of the Bureau's documents is our own, and does not reflect Southern Weighing and Inspection Bureau policy.

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SOUTHERN WEIGHING AND INSPECTION BUREAU

REQUIREMENTS
FOR THE APPROVAL OF
BELT CONVEYOR SCALES

CIRCULAR 9585-5

ISSUED:
JUNE 1, 1971

ISSUED BY:
C. E. Pike, Manager
Southern Weighing and Inspection Bureau
Suite 306 - Transportation Building
151 Ellis Street, N. E.
Atlanta, Georgia 30303

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3	Vanders Obligation
3	Tests - Types Defined
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BUREAU
REQUIREMENTS FOR BELT SCALES

1. The system must be designed and rated so that material flowing over the scale will remain within 50% to 98% of scale capacity and must be adequate and constant.

2. All conveyors on which a belt scale is located must be rigid in design and so constructed that it is free from vibration and is not subject to stress that would cause any deflection and shall not exceed 1,000 feet in length from center of head pulley to center of tail pulley.

③ 3. All conveyors on which a belt scale is located must be equipped with a gravity take-up that is of adequate weight so as not to allow slippage of the belt on the drive pulley. With such weight properly weighted, the belt must remain in contact, with all troughing weigh bridge idlers or sensing elements, at all times.

4. The conveyor on which the scale is located must be free from interference from all other operations.

④ 5. The system must be so designed that the complete contents of each individual car may be guaranteed to pass over the scale.

6. Sufficient impact idlers must be provided in the conveyor under each infeed so as not to cause a deflection of the belt during the time material is being introduced.

⑤ 7. Incline of the scale conveyor belt must not be in excess of 18 to 20 degrees.

8. For maximum reliability, mechanical scales should be equipped with a multi-idler suspension.

9. Adequate simulated load testing equipment, to be applied on the belt over the weight sensing element, approximating 80% of the rated capacity of the weighing system, is required. A suitable storage area must be provided so that such equipment does not rust or deteriorate from abrasive or coating action. Note: See Standard Procedure for Test of Belt Scales. (Page 5 - No. 17)

① 10. A rate of flow indicator must be installed and correctly calibrated. The indicator must also be equipped with a twenty-four hour disc or strip chart to serve as a permanent record, along with a high and low cut-off alarm system. This is to help prevent under or overloading of the scale. The alarm should be operational at not lower than 35% or greater than 98% of scale capacity. The type of alarm used (i.e. audio or visual) must be determined by the merits of each individual application. Such system will not be outfitted with a switch to disconnect either the chart or alarm system. Any exceptions to this rule will be at the discretion of the Bureau.

① 11. A fast-count totalizer must be installed and must register in units of 1/10 of a ton, or as determined by this Bureau.

12. A ticket or tape printer (determined by each individual application) and printing to the equivalent numerals as indicated in No. 11, must be installed. It is essential that the printer mounting will guarantee vibration free operation.

② 13. Scale and instrumentation cabinets must be purged with clean dry air.

14. Where scales and component parts are subject to a rapid or extreme change in temperature, heaters must be installed as suggested by manufacturer.

15. Scales located near large bodies of water, operations that require use of quantities of water, or any area of high humidity, must have heaters installed in scales and/or instrumentation as suggested by manufacturer.

16. Scales and especially instrumentation should be protected from the elements by weather-proof structures. Control rooms that house instruments must be air purged with air conditioning, fans with filters, heaters, etc. so that a dust free area of greater density must be created on the inside than is outside. Such system is required to preserve all electronic instruments.

17. Wind screens must be erected around the entire weighing element.

18. Adequate access to scale must be provided. This includes a walk-way, step, etc. so that servicing can be accomplished with ease.

① 19. Sufficient guards must be erected around "live" scale parts located near walk-ways so that persons will not touch such parts or deposit equipment in their vicinity. Such application will be at the discretion of this Bureau.

① 20. In some cases, "live" parts of scales should be painted in contrasting colors so as to warn persons against touching them. The application of this Rule will be at the discretion of this Bureau.

21. Hydraulic machinery, large motors, or any equipment which will cause excessive vibration or noise is prohibited from being placed in, or affixed to, the control room.

22. All infeed gates, feeders, etc. must be positive in action and so designed that material will flow freely through them when opened or placed in operation. They must also be positive in their closing action so that leakage does not occur.

① 23. Scale housing and instrumentation must be securely locked.

TOLERANCE VALUES

⑥ 1. Material Test Tolerance

All belt scales must be material tested and adjusted to within 0.25% with repeatability. The spread between plus or minus figures shall not exceed 0.25%.

⑥ 2. Maintenance Tolerance

All belt scales must maintain a 0.5% tolerance between material tests. The spread between plus or minus figures shall not exceed 0.5%.

⑥ 3. Zero Tolerance

All belt scales must maintain a zero balance of 0.01% for 10 minutes before use, and after sufficient warm-up of the belt.

⑥ 4. Repeatability Tolerance

All belt conveyor scales using simulated load testing equipment must be tested for a repeatability of not greater than 0.1% for at least 5 consecutive tests. The spread between plus or minus figures shall not exceed 0.1%.

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ADDITIONAL REQUIREMENTS

1. A spare parts kit, as suggested by manufacturer, must be kept on hand at all times, with replacement of any parts used as soon as possible.

Note: This requirement is not intended as a means to heavily stock the scale owner with unnecessary and expensive parts, but is intended to be of an assistance. Such Kit is to contain only parts that can be easily replaced or installed by the owner, and not an electrical or scale technician.

2. A service contract, preferably with the scale manufacturer's service representative, must be evidenced. Such contract must provide for at least one yearly overhaul of scale.

3. At least two persons or more on location must be thoroughly familiar with the scale and its operation.

4. Control over entire system must be exercised by the scale operator to insure adequate loading of the weighing device.

5. Unauthorized personnel should be discouraged from loitering in the scale and instrumentation areas.

6. Where test chains are used, adequate cables, bridles, hooks, etc. must be provided to hold the chains in place on the belt as recommended by the scale manufacturer.

①

VENDER'S OBLIGATION

IT SHALL BE THE DIRECT OBLIGATION OF THE PERSON OR FIRM SUPPLYING A BELT-CONVEYOR SCALE TO THE USER TO CONTACT THE SOUTHERN WEIGHING AND INSPECTION BUREAU AS FAR IN ADVANCE OF THE TESTING DATE AS POSSIBLE. IN ORDER TO EXPEDITE SUCH TESTS, IT IS SUGGESTED THAT THE BUREAU'S GENERAL OFFICE BE CONTACTED AS SOON AS DEFINITE PLANS HAVE BEEN MADE FOR THE INSTALLATION OF THE SCALE. FURTHER, AFTER INSTALLATION, THE PERSON OR FIRM SUPPLYING THE BELT-CONVEYOR SCALE MUST ATTEST (IN WRITING) TO THE FACT THAT ALL THE AFOREMENTIONED RULES, REGULATIONS, AND CONDITIONS HAVE BEEN MET, AND THAT THE SCALE IS WEIGHING WITHIN TOLERANCE. ONLY WHEN THE USER HAS BEEN SO INFORMED AND A COPY OF THE VENDER'S LETTER HAS BEEN FURNISHED TO THE SOUTHERN WEIGHING AND INSPECTION BUREAU SHALL THE BUREAU BE NOTIFIED THAT THE WEIGHING SYSTEM IS READY FOR TESTING.

TYPES OF TESTS DEFINED

⑦ Material Testing

1. All belt conveyor scales must be material tested before acceptance. Three to five such tests are required, with 10 to 15 car (or in some cases heavy truck) loads per test. If the weighing system is designed for individual car weights, the weight of each individual car must be in tolerance. Results must be furnished this Bureau.

① Maintenance Testing

2. All belt conveyor scales must be maintained within a 0.5% tolerance between material tests, by using a known weight load test. Such tests must be conducted on a weekly basis, preferably as soon after actual use of the belt as possible. Results of each test must be furnished this Bureau.

Repeatability Test

3. All belt conveyor scales must be tested for repeatability each time a Maintenance Test is made and before Material Tests are run.

STANDARD PROCEDURE FOR TESTS OF BELT SCALES

1. Scale and entire installation will be checked for conformity with the above listed rules and regulations. The scale and all component parts must be completely installed and in good operating condition before any tests will be made.

⑧ 2. The belt length, belt speed, and weight of chains per foot must be accurately measured so as to determine tons per foot of belt travel during chain tests.

3. The belt must be run at least twenty minutes before test begins in order to warm it up. At temperatures below 40 degrees, the warm up time should be of longer duration.

4. Following warm-up, belt must be run for at least ten minutes to determine zero of scale. During this time, the zero reading should be constant.

⑧ 5. After establishing that the scale holds its zero, ten circuits of the belt will be run with the simulated load testing equipment in place on belt. In some instances, where the belt is long, only three circuits of the belt will be required.

If test chains are used, they shall be held securely in place on the belt as the scale manufacturer recommends.

① If tests utilizing other than the above methods are contemplated, the approval of the Bureau must be secured.

② Note: When other than test chains are used, only idlers of the highest quality and requiring lubrication daily, must be used. Such idlers must be installed on the weighing element and for at least five idler spaces before, and for at least five idler spaces after the weighing element. Further, each week correct idler level must be determined with a string level. If any one, or more, of the above named idlers are out of level, the scale must not be used until correction is made. Idlers with worn bearings must be replaced.

⑥ 6. Five more simulated load tests must then be run, with results of each test reading within 0.1% of the first test outlined in No. 5. This will establish repeatability.

⑥⑦ 7. If the scale has repeatability, fifteen loads will then be weighed over the scale, at 50% to 98% of capacity. A load is construed as a rail carload or truck load of high capacity. (Note: In instances where procurement of rail cars proves difficult, ten loads per test may be substituted.) This is a calibration test and may have to be made several times in order to bring the weighing device within the acceptable tolerance of 0.25%.

⑥⑦ 8. After the scale has been properly calibrated, three separate material tests, all within 0.25% with material being loaded at 50% to 98% of capacity, must then be made. Each test will consist of fifteen loads. (Here again ten loads per test may be substituted in the event rail cars are difficult to obtain.)

9. Following three successful material tests, five simulated load tests must again be made in order to establish a new calibration factor.

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10. On successful completion of all tests, the scale will again be checked for zero. At this time, it will also be established that a service contract has been consummated with a qualified belt scale service organization, preferably the scale's manufacturer.

① 11. Material scale tests should be made once every 90 to 120 days, or as directed by the Bureau.

⑥ 12. The material acceptance tolerance of 0.25% must be maintained for thirty days, and at any time the scale is overhauled or material tested by an authorized scale man.

⑥ 13. A maintenance tolerance of 0.5% must be maintained by the user at all times after the scale is accepted. This may be assured by conducting tests at least once a week, as outlined in No. 9, using the newly established calibration factor.

⑦ 14. The rail carrier should be contacted at least two weeks before material tests are made to insure that sufficient cars are available.

① 15. Copies of weekly tests must be sent to the General Office of this Bureau. Also, copies of the results of the scalemen's tests must be sent to the General Office of this Bureau every time they are made.

16. Proof of weight for accepted and certified belt scales will be in the form of a printed weight ticket. The rate of flow chart must be dated corresponding with cars in loading or unloading sequence. The correct rate of flow over a belt scale is essential for good weights.

All of the records outlined herein must be preserved together so that they may be audited under terms of the weight agreement.

① 17. In instances where material testing can be satisfactorily performed weekly, Simulated Load Tests are not required. Copies of weekly material tests, however, must be submitted to the General Office of this Bureau.

* * * * *

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AN EXPLANATION OF

RULES FOR THE INSPECTION, TESTING, AND CALIBRATION
OF
BELT CONVEYOR SCALES

* * * * * * *

Southern Weighing and Inspection Bureau
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C. E. Pike, Manager
July 16, 1973

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BELT CONVEYOR SCALES

There are four basic types of continuous weighers which are known as belt or conveyor scales. These are: Mechanical, Electronic, Atomic, and Pneumatic.

Basically, all types except atomic operate on the principle of material passing over a weighing element on a belt conveyor. By integrating the speed of the belt with the scale indication, tons (or pounds) per an hour are produced. Atomic scales, on the other hand, are actually measuring devices. They operate by placing a radio active mass over the belt and a form of radiation counter under the belt. Usually a foot (or more) of pre-weighed material is placed on the belt under the radio active mass and the radiation counter counts the number of rays not absorbed by the material. This in turn is translated or "calibrated" into tons (or pounds). As with the other types of scales, the speed of the belt is integrated with the weight indication to produce tons (or pounds) per hour.

INSPECTIONS

Rate of Flow: By experience it has been found that belt conveyor scales only produce reliable weights when the material flow is constant between 50% and 98% of scale capacity. Valley (pits), slugs, and other interruptions in an otherwise even flow can produce erratic weights, as can long tailing or dribbles from the feeders.

② Stability of Scale: One of the basic laws of weighing machines is "plumb and level" and belt conveyor scales are no exception. Although the conveyor belt might be on an incline, the basic weighing system is plumb and level. Therefore, not only should the conveyor be stable but adequate bracing should be maintained under the scale to prevent vibration or movement.

② Tension: One of the greatest forces that will affect belt conveyor scales is tension. A scale belt cannot be too tight and by the same token the belt must not be too loose. The very best way to insure even tension is with the use of a gravity take-up. This is a weight suspended on a roller from the underside (return side) of the belt. The weight must be free in its movements and not bind on guide rails when they are used. Another type of gravity take-up usually used when limited space is a problem is to mount the rear pulley of the belt on a movable carriage. A bridle and cable are then affixed to the rear of the carriage, with a weight being affixed to the other end of the cable. With the use of pulleys the weight can be hung from a wall or other convenient place. In both cases only enough weight is used so that the belt will not slip on the drive pulley while under load. If the belt sags between idlers, the idler spacing must be changed. Under no circumstances should excessive belt sag - under load - be countered by increasing the gravity take-up-weight. This would create too much tension and could cause massive errors.

Conveyors: All conveyors used in connection with belt conveyor scales should be rigid in design and should be used for weighing only. Additionally, all material must pass over the scale. Trippers, etc. must not be installed in the belt. Further, the slope of the conveyor should not exceed 18 to 20 degrees; otherwise, the material would tend to roll back down the belt causing some material to be weighed more than once. Flited conveyor belts (belts with ridges molded onto working surface) should not be used as calibration is extremely difficult.

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⑨ Testing Equipment: Almost all belt conveyor scales are installed with testing equipment. Atomic scales employ a calibrated plate which absorbs a given (or known) amount of radiation. Other types of scales are calibrated with anything from test weights, logging chains, etc. to test chains. The only practical method found thus far has been with test chains. In reality, a test chain is not a chain but a series of rollers connected together with links and calibrated to the nearest thousandth of a ton (or pound) per foot. These so-called test chains provide the nearest simulation to a loaded belt and reproduce not only weight but attempt to form the belt configuration under load. Use of test weights, logging chains, etc. has not proved satisfactory and for this reason are unacceptable.

Totalizer: All belt conveyor scales are equipped with a master totalizer which shows the total tons (or pounds) weighed. Weight indication for test purposes should only be taken from the master totalizer. Some belt conveyor scales are also outfitted with a percentage rate of flow meter as part of the master totalizer instrumentation, while others supply this unit as an accessory.

Alarms: Since almost all belt conveyor scale instrumentation is located in the same area as other controls (control room), the operator's attention to the rate of flow chart cannot be constant. Therefore a high and low cut-off alarm system must be installed to attract the operator's attention. The low alarm should be operational from 0 to approximately 35% of scale capacity; and the high alarm should operate at approximately 98% of scale capacity. This is to alert the operator that the scale is loaded to a point below its capacity to register weights correctly or when the scale is at the point of being overloaded. It should be borne in mind that the type of alarm to be used (audio or visual) depends on the noise level and presence of other warning lights in the control room. Certainly, the type of alarm used must be such that it will be immediately noticed by the operator. Additionally, it is advised that the alarm system not be equipped with a cut-off switch or time delay device.

Instrumentation: Control rooms or areas should also receive close attention. Since usual proof of weight is in the form of a printed weight ticket, the scale should be equipped with a printer. Additionally, since it has been proved that belt conveyor scales only produce accurate weights when loaded between 50% and 98% (to 100%) of capacity, a rate-of-flow disc or strip recorder is also necessary. The printed ticket and the recorded rate-of-flow chart then comprise proof of weight for belt conveyor scales.

Air Purging and Heaters: Dust and moisture are two problems that always affect instrumentation; therefore, the control area is required to be air purged with air conditioning and heating equipment (as the season demands). This is to create an area of greater density inside the instrumentation area than is outside. By these means dust is held to a minimum. By the same token, scales having cabinets must also be air purged and equipped with thermostatically controlled strip heaters. (One or more light bulbs placed in cabinets are not sufficient.)

Wind Screens: All conveyors not located in buildings on which a belt conveyor scale is used must be outfitted with wind screens. Wind screens are merely walls (of metal, wood, etc.) placed around the weight sensitive area (20 feet before and 20 feet after the weight sensitive element, including the weight sensing element). Such screening must also include a roof and doors at least at one end. The purpose is to keep the effects of wind to a minimum. Since the scale and testing equipment should also be protected from the elements, the wind screens serve a dual purpose.

Live Scale Parts: All "live" parts of the belt conveyor scale near walkways or where they can be reached should be outfitted with guards so that such parts can't be accidentally touched. Such parts should also be painted in a bright contrasting color so that everyone will immediately recognize them for what they are. Additionally, easy access must be made to all scale parts so that the scale can be observed while in operation and servicing can be accomplished with minimum difficulty.

Location of Machinery: Large motors, machinery, or hydraulic equipment should not be affixed to the scale conveyor or control house, as excessive vibration and/or harmonics could cause malfunctions in the rate-of-flow chart, printer, integrator, etc.

Infeeds: Infeeds to conveyor belts should receive special attention, as they could become troublesome. Feeders, gates, etc. must be positive in action and must not leak. Long dribbles before weighing commences or long tailings after the gates close can only produce inaccurate weights. Additionally, the conveyor belt under the infeeds must not sag excessively under impact of material being introduced. If this situation exists, only the placement of more idlers (or impact idlers) in the affected area will cure the problem.

Scale Housing: All belt conveyor scales utilizing cabinets over or beside the belt must be securely locked to prevent tampering from unauthorized persons. Cabinets located elsewhere should also be locked for the same reason. Keys should be in the possession of the top official at the site, or only one other person he so designates.

② Idlers and Pulleys: The sensitive area of weighing on this type of scale is approximately twenty feet before and twenty feet after the weight sensing element. In this area, idler spacing must be exact and alignment must be true. An out-of-round idler will introduce errors which cannot be factored out of the scale. Restrictions must be placed on the use of training or trueing idlers, as they can introduce adverse tension into the belt. Wing pulley use should be discouraged as too much vibration to be compensated for is usually present.

Conveyor Belting and Splices: All splices should be of the vulcanized type; however, one good metal splice can be used in most cases. The reason for this provision is because most splices (other than vulcanized) tend to create heavy spots in the belt, making calibration difficult. It should also be borne in mind that the higher rated scales usually utilize heavy multi-ply belting. Since belting must be as flexible as possible to achieve good weights, it is necessary to run the belt for a minimum of twenty minutes empty before use.

⑩ Conveyor Length: Conveyors on which a belt conveyor scale is located must not exceed 1,000 ft. in length, from center of head pulley to center of tail pulley. By the same token, conveyors under 50 feet should receive the explicit approval of the scale manufacturer before attempting to make tests. Long conveyors tend to make the zero calibration very difficult, if not impossible. Short conveyors, unless specifically designed for the job, can cause uneven tension, rapid idler bearing wear, etc.

Chutes and Surge Bins: The discharge chute and/or surge bin should be carefully inspected. Chutes that spew material out over the sides of cars are unacceptable. This condition can usually be cured by placing metal guides in the chute trough so that the stream is concentrated. On large operations (that load at better than 1500 tons per hour), a surge bin must be placed at the discharge end of the belt. This is a collecting bin equipped with a gate and loading chute. With this equipment the loading can be uniform with no spills between cars. The best "rule of thumb" to determine size of the bin is to: estimate the rate of flow per minute; times the minutes required to move the rail cars 20 feet; plus 10%. Usually bin capacity is rated on approximately three minutes running time. Therefore, a system rated at 3000 TPH will be equipped with a bin of 150 ton capacity.

Discharge: The discharge end of the conveyor belt should also receive close attention. Some types of material tend to cling to the belt or leave a residue. As this material or residue builds up, the belt becomes heavier, thereby affecting the zero calibration of the scale. Also, when this condition exists, it is usually found that when the material or residue forms a thick enough layer, parts of it will "sluff" off, thereby creating an erratic load situation on the belt, not to mention uneven tension. It is strongly suggested that a gravity type wiper be installed at the end of the belt on the return side (underside).

Sinks, Pits, or Dumping Areas: When belt conveyor scales are used to weigh inbound commodities, special attention must be given the device into which the material is dumped from rail cars. The sink or pit must be so designed that the complete contents of a rail car enter that area only and are not spilled outside the intended sink or pit. Grating must contain holes of sufficient size to guarantee the passage of the complete contents of the car. Sides of the pit must also slope sufficiently so that all material flows to the feeder gate. When practical, the unloading area must be enclosed to prevent wind-blown loss and detrimental effects from the forces of nature.

② Scale Location: Location of the scale on the conveyor belt is a problem for the scale supplier and system owner; however, it is well to know where a scale will produce the best weights. As a "rule-of-thumb", a belt conveyor scale will work better as near to the in-feed as possible. It should be remembered that this will be at least twenty feet, unless the scale company has made specific provisions to move the weight sensing element closer. Also, a scale must not be placed in a concave or convex curve of the conveyor. This is to insure complete contact of the belt at all times with the weight sensing element and to prevent excessive tension in the weighing area.

①

VENDER'S OBLIGATION

IT SHALL BE THE DIRECT OBLIGATION OF THE PERSON OR FIRM SUPPLYING A BELT-CONVEYOR SCALE TO THE USER TO CONTACT THE SOUTHERN WEIGHING AND INSPECTION BUREAU AS FAR IN ADVANCE OF THE TESTING DATE AS POSSIBLE. IN ORDER TO EXPEDITE SUCH TESTS, IT IS SUGGESTED THAT THE BUREAU'S GENERAL OFFICE BE CONTACTED AS SOON AS DEFINITE PLANS HAVE BEEN MADE FOR THE INSTALLATION OF THE SCALE. FURTHER, AFTER INSTALLATION, THE PERSON OR FIRM SUPPLYING THE BELT-CONVEYOR SCALE MUST ATTEST (IN WRITING) TO THE FACT THAT ALL THE AFOREMENTIONED RULES, REGULATIONS, AND CONDITIONS HAVE BEEN MET, AND THAT THE SCALE IS WEIGHING WITHIN TOLERANCE. ONLY WHEN THE USER HAS BEEN SO INFORMED AND A COPY OF THE VENDER'S LETTER HAS BEEN FURNISHED TO THE SOUTHERN WEIGHING AND INSPECTION BUREAU SHALL THE BUREAU BE NOTIFIED THAT THE WEIGHING SYSTEM IS READY FOR TESTING.

The purpose of this requirement is threefold: to protect the buyer; to protect the seller; and to protect the carrier. The scale supplier may refuse a letter stating that the belt conveyor scale system is correct and in good weighing condition, until all conditions are such that good weights can be achieved. On the other hand the buyer is guaranteed that the system will produce good weights. Lastly, the carrier or its representative does not have unnecessary expenditures in weighing cars, traveling and living expenses of its representatives, and wasted time in testing when the system is not cabable of producing reliable weights.

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Testing Belt Conveyor Scales

There are two types of tests used to calibrate belt conveyor scales: simulated load tests; and material tests. Of the two, the best way (and the only acceptable method) is the material test.

Material Test: After finding that all conditions comply with rules for belt conveyor scales a material test is made. (This test consists of moving previously weighed - or material to be weighed - over the belt conveyor scale. Extreme care must be taken to see that all material is weighed both on the check weigh scale and on the belt conveyor scale. Then the two weights are compared, the difference figured, and the error in percentage computed.)

1. The check-weigh scale (track scale, truck scale, etc.) is checked to determine that it is in good condition and has been calibrated.

2. The scale conveyor belt is run for twenty minutes or more (at below 42 degrees the belt should be run for 60 minutes).

3. A short meeting should be held with all personnel at the conveyor scale site to explain what is to happen.

4. After running the belt empty (warming up the belt), a reading is taken from the master totalizer.

⑥⑪ 5. The belt is run for approximately 10 minutes and the reading is again taken. It should not vary more than one increment of the scale. If the reading varies more, the zero must be adjusted. This process is repeated until an acceptable zero condition is achieved.

6. After taking the master totalizer reading, material is introduced onto the scale belt and the rate of flow should be carefully observed to rise to better than 50% of rated capacity. The ideal operating and weighing range is 77 to 85 percent of rated capacity. (As a rule of thumb, if the time the scale operates after the infeed is opened and closed at under 50% capacity is no more than 10% of the running time, acceptable weighing conditions are present.)

7. After the weighing has been completed, the belt should be running and empty. (The belt should not be stopped.)

8. The reading is then taken from the master totalizer again. The "start" figure is subtracted from "stop" figure, which shows tons (or pounds) weighed. This figure is compared with the printer. The printer may show as much as two of the smallest increments difference, which is permissible.

⑦ 9. Since three to five tests are required, the other tests are then made, following the same procedure as above.

10. When all tests have been completed and the material has been weighed on the check weigh scale, the percentage error is computed. The check weigh scale must always be considered the "K" factor (or constant) with the belt conveyor scale being calibrated to it. (Note: In all cases, the cars or trucks must be both light weighed and gross weighed on the same scale. Weights taken from two different scales should not be used, and in every test the cars or trucks must be light weighed. Also, weighings must be made to the smallest increment of the weight indicator.)

Simulated Load Test of Mechanical Belt Scales: The scale and all component parts must be thoroughly inspected to determine that compliance with the rules has been met.

A simulated load test is used as a reference only and should not be considered as a calibration test. The following are the steps to be taken for a simulated load test of a mechanical belt conveyor scale.

1. Measure the exact length of the conveyor belt on the belt center to the nearest 1/10 foot.

2. Find the stamped weight per foot on the test chains (usually at or near the end of the chain on a brass plate). When more than one chain is used, add the weights per foot.

3. Run the conveyor for at least twenty minutes. (Below 42 degrees the conveyor should be run for 60 minutes.)

4. Take the reading from the master totalizer and run belt for ten minutes.

5. Take the reading again and compare. If the reading varies by more than one increment, the scale should be adjusted for "zero". This process should continue until the final adjustment proves the scale to be holding zero.

6. Stop the conveyor and apply test chains, the center being over the center of the weight sensing element. Bridles made of cable or heavy rope should be affixed to the ends of the chains to securely hold them in place on the belt.

7. The conveyor should be run several circuits to center the chains on the belt. Adjust the bridle if necessary.

8. Select one idler at the scale and mark it as the reference point.

9. Mark the side of the belt and run three complete revolutions and stop the belt when the mark exactly crosses the center of the marked idler. Mark the belt again exactly opposite the reference point.

10. Read the master totalizer to at least 3 decimal places.

11. Run the conveyor (10 circuits for a short belt and 3 circuits for a long belt). Stop the conveyor when the first mark passes the center of the reference point idler.

12. Read the master totalizer.

13. Mark the belt exactly in the center of the reference point idler.

14. Measure the over-run or under-run from the mark in the latter part of (9).

15. The number of circuits of the belt times the number of feet in one circuit (length of belt) plus or minus the over-run or under-run gives the length the belt traveled. Multiply this by the weight per foot of test chains (see Item 2). The resulting figure is total weight. Convert the resulting figure to tons (or pounds), if necessary, by dividing the scale registration unit. Compare the results with the results of subtracting (10) from (12).

16. Run this same test the required number of times (at least three tests or at least five if excessive errors are shown).

6.

Electronic scales should be tested as follows:

Since electronic scales are equipped with a switch which can disengage the integrator, measuring over-runs or under-runs from the belt is not necessary. The scale operator merely runs the belt and engages the integrator as a mark on the belt passes a reference point. When the belt has run the desired number of circuits, the switch is again activated to disengage the integrator as the mark on the belt passes the reference point. Therefore, Items 1 through 13 should be followed as should Item 16.

Other Suggested Steps to be Taken:

1. Since a belt conveyor scale must have repeatability (ability to repeat the same indication when the same test load is applied successively) it is wise to conduct at least three simulated load tests before the initial material test is made. If such tests prove the scale does not have repeatability, further testing would be impractical as the scale would not be capable of weighing correctly.

2. If a belt conveyor scale has been calibrated to test chains before material testing, and it is necessary to further adjust the scale to the material tests, it then proves the test chains are not in calibration with the weighing system. It would be necessary to then conduct at least five simulated load tests following the material tests. These chain tests would produce an error. The errors should then be averaged to produce a calibration factor. If this factor is plus a certain percentage, then such a factor should be subtracted from future chain tests. By the same token, if the factor shows minus a certain percentage then such a factor should be added to future chain tests.

3. Because material tests are considered the only satisfactory means to calibrate a belt conveyor scale, simulated load tests are only considered as a reference point. In order to show that the belt conveyor scale is holding its calibration, weekly simulated load tests should be made and reports of such tests should be furnished to the person responsible for supervision of the scale. By this means, monitoring of the weighing system is possible on a weekly basis without incurring the expense of railroad weighing.

⑦ 4. When weekly tests show that the belt conveyor scale is not out of calibration more than 0.5%, material tests consisting of ten to fifteen cars (or trucks) may be made only once every six months. When the material being handled leaves a residue on the belt, such as wood chips, the material tests should be made approximately once every 90 days, not to exceed once every 120 days.

5. It is advisable whenever practical to have the check-weigh scale tested and inspected before material tests are made.

6. Before final approval is given to any belt conveyor system, the user should provide evidence that at least two inspections will be made each year by a qualified scale service man. Of these visits, at least one should include a complete overhaul.

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Definition of Terms Used in connection with Belt Conveyor Scales

Air Purge: The act of creating an atmosphere greater on the inside than outside, using clean dry air, to discourage dust and other foreign matter.

Belt Conveyor: An endless moving belt for transporting material from place to place. *

Belt Conveyor Scale; (Belt Scale); (Conveyor Scale): A device installed on a belt conveyor to measure the weight of bulk material being conveyed. *

Bend Pulley: A roller placed on the return side (underside) of a conveyor belt to turn its direction or to measure speed of belt.

Cable Conveyor: A belt conveyor utilizing cable or rope as the supporting member for the conveyor on which the idlers are mounted.

Calibrated Plate: A suitable metal plate, provided by the scale manufacturer, determined to have the same effect on a nuclear scale as a specified load or bulk material on the belt conveyor. A calibrated plate is the equivalent of a test chain or test weights used with other types of belt conveyor scales. *

Chain: See Test Chain.

Chart Recorder: A device used with a belt conveyor scale which records the rate-of-flow of bulk material over the scale at any given time. A recorded chart together with a record of weight constitutes proof of weight.

Concave Curve: A change in the angle of inclination of a belt conveyor where the center of the curve is above the conveyor. *

Convex Curve: A change in the angle of inclination of a belt conveyor where the center of the curve is below the conveyor. *

Conveyor Stringers: Support members for the conveyor on which the idlers are mounted.

Counter (Remote): A numerical display in a location remote from the scale showing the tons (or pounds) of material that have been conveyed over the scale.

Disc Chart: See Chart Recorder.

Drive: The device or apparatus used to transmit energy from a motor to move the conveyor belt.

Feeders: See Infeed.

Gate: See Infeed.

Gravity Type Wipers: A scraping or wiping device used to clean residue from the belt on the return side (underside) of the belt in the vicinity of the head pulley. The wiper is affixed to one end of an arm which has a weight hanging from the other end. The weight is such that the wiper is held against the belt.

Head Pulley: The pulley at the discharge end of the belt conveyor. The power drive to drive the belt is generally applied to the head pulley. *

Idler Space: The center-to-center distance between idler rollers measured parallel to the belt. *

Idler Frame: The frame or device which holds the idler rollers, affixed to the conveyor stringers.

Idler or Idler Rollers: Freely turning cylinders mounted on a frame to support the conveyor belt. For a flat belt the idlers may consist of one or more horizontal cylinders transverse to the direction of belt travel. For a troughed belt, the idler will consist of one or more horizontal cylinders and one or more cylinders at an angle to the horizontal to lift the sides of the belt to form a trough. *

Infeed: The gate, short belt, vibrator feeder, stroker feeder, etc. that deposits material on the belt conveyor to be weighed.

Integrator: The "heart" of the belt conveyor scale. A device which integrates the speed of the belt with the weight of the material to produce tons (or pounds) per hour. The integrator may be electronic or mechanical and may be one of numerous patented designs.

Loading Point: The location at which material to be conveyed is applied to the conveyor.

Master Totalizer: See Totalizer.

Nuclear Type (non-contract) Scale: A device consisting of a source of nuclear radiation and a detector for that radiation. Absorption of radiation determines the mass of the material passing between the source and the detector. *

Printer: A device used to imprint on tickets, tape, or other papers, the tons (or pounds) of material that have passed over the scale in a given time. (Such as per car or per train weights.)

Pulley: A cylindrical roller over which the belt passes to change direction, such as the head pulley or tail pulley or bend pulley.

Rate of Speed Detector: A device usually operated in conjunction with electronic load cell belt conveyor scales which transmits the speed of the belt to the integrator. Several types are in use, the most popular being either a small generator whose voltage output is in direct relationship to the speed of the belt; or a slotted disc mounted between a photo electric cell and light source which converts each pulse of light to an electronic signal to the integrator.

Rated Capacity: That value representing the weight that can be delivered by the device in one hour. *

Registration: The unit of weight in which the scale is calibrated, such as 5,000 lbs., tons, long tons, metric tons, etc.

Rope Conveyor: See Cable Conveyor.

Simulated Weight Test: A test using artificial means of loading the scale to determine the performance of a belt conveyor scale. *

Skirting: Stationary side boards or sections of belt conveyor attached to the conveyor support frame or other stationary support to prevent the bulk material from falling off the side of the belt. * Usually used at infeeds.

Stringer: See Conveyor Stringer.

Strip Chart: See Chart Recorder.

Strip Heater: A thermostatically controlled heating strip (usually of the Calrod type) used to heat the scale or component parts sufficiently to prevent condensation.

Swedged Pulley: A drive pulley with a vulcanized rubber coating molded in a high friction pattern to prevent slippage of the belt under load.

Swivel Idler: An idler frame pivoted in its center to the idler stringers so that it may change position. Tracking idlers are mounted beside the troughing idlers so that if the belt rides off center the pressure on the tracking idler forces the swivel idler to turn, thus realigning the belt on the conveying idlers.

Tail Pulley: The pulley at the opposite end of the conveyor from the head pulley. *

Take-up: A device to assure sufficient tension in a conveyor belt that the belt will be positively driven by the drive pulley. A gravity take-up consists of a horizontal pulley free to move in either the vertical or horizontal direction with the dead weights applied to the pulley shaft to provide the tension required. A jack or screw type take-up consists of a device that must be manually adjusted to move the tail pulley to increase or decrease tension. A hydraulic take-up consists of hudraulic cylinders mounted on either side of both ends of the tail pulley. When properly activated, the hydraulic cylinders will move the tail pulley to increase or decrease tension on the belt.

Take-up Guides: Guides or tracks on either side of the counter weight to prevent vertical movement of that weight.

Test Chain: A device consisting of a series of rollers or wheels linked together in such a manner as to assure uniformity of weight and freedom of motion to reduce wear, with consequent loss of weight to a minimum. *

Totalizer: A device used with a belt conveyor scale to indicate the weight of material which has been conveyed over the scale. The master weight totalizer is the primary indicating element of the belt conveyor scale. An auxiliary vernier counter used for scale calibration is not (necessarily) part of the master weight totalizer. Auxiliary remote totalizers may be provided. The totalizer shows the accumulated weight and may be non-resettable or may be reset to zero to measure a definite amount of material conveyed.

Tracking Idlers: Usually small cylinders vertically mounted on shafts affixed to a swivel idler frame. The purpose is to allow the side of the belt to rub against the tracking idler, forcing the swivel idler frame to turn, thus realigning the belt.

Training Idlers: Idlers of special design or mounting intended to shift the belt sideways on the conveyor to assure the belt is centered on the conveying idlers. *

Tripper: A device for unloading a belt conveyor at a point between the loading point and the head pulley. *

Wing Pulley: A pulley usually used as the tail pulley, made of widely spaced metal bars in order to set up a vibration to shake loose material off the underside (return side) of the belt. The use of such a pulley is definitely not recommended unless the conveyor stringers under the scale are thoroughly braced with their own support.

Wiper: See Gravity Type Wiper.

(*) Taken from NBS H-44.

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CHAIN TEST

(1) Run belt for 20 minutes when temperature is above 42°; 1 hour when temperature is between 32° and 42° ; for as long as possible more than 1 hour when temperature is below freezing.

(2) Take scale reading, and 10 minutes later take reading again. If scale is on "zero", reading will be the same. If not, adjust "zero" and repeat above procedure until no movement of read out is detected.

(3) Look at plate on chains and determine weight per foot.

(4) Measure belt to nearest inch or 1/10 foot.

(5) Place chains on belt and tie down.

(6) Select one idler as a reference point and mark three long stripes on side of belt opposite idler. Start belt running.

(7) Multiply length of belt times chain weight per foot and divide by 2000 to determine tons per 1 revolution of belt. This is the K(1) factor.

(8) Divide K(1) by belt length to determine tons per foot. (If an inch rule is used, divide above result by 12 to determine weight per inch.)

(9) Multiply K(1) by number of circuits of belt to be run to determine K factor.

(10) When the last of the three stripes on the edge of the belt pass the reference idler, shut off the belt. Mark a spot on the belt opposite the reference idler and further mark the direct center in a contrasting color, i.e., yellow or white mark with a pencil line in the direct center.

(11) Write down the scale reading.

(12) Run the belt the required number of circuits and on the last circuit, when the last of the three stripes passess the reference idler shut off the belt.

(13) If the previous mark does not perfectly align itself with the center of the reference idler, again mark the edge of the belt and locate a contrasting line directly in the center. Measure the distance between the marks. If an overrun, it is a "plus"; if an underrun, it is a "minus". Multiply the measurement by the K factor for feet or inches, as the case may be. This produces tons over/underrun.

(14) Read scale and subtract (11) from it.

(15) If overrun was noted, subtract tonnage from reading; if underrun, add tonnage to it.

(16) Compare results with K factor. If K factor is the larger of the two figures, the resulting error is "minus"; if the K factor is the smaller of the two figures, the resulting error is "plus".

(17) Determine error percent by dividing K factor into error tonnage. (Be sure to move decimal point 2 places to right in computations.)

(18) Repeat steps (11) through (17) at least two more times to determine error repeatability. When error has been determined, adjust scale span as per directions from manufacturer. Note: Each time step (13) is repeated, remove old centerline mark on over/underrun so as not to confuse future measurements.

(19) If adjustment to span was made, repeat steps (11) through (18) at least three times to determine adjustment was correct and scale is in correct calibration.

(20) The best possible time to run a chain test is immediately after material handling has taken place so that belt is in proper flexible condition.

* * * * * * *

Atlanta, Georgia,
March 17, 1975.

ANNOTATIONAL COMMENTS

① Requirements for reporting to the Bureau or for adhering to the Bureau's regulations apply only to devices falling under Bureau jurisdiction. The appropriateness of a given data requirement or regulation must be determined for each situation not governed by the Bureau or the regulatory organization.

② Items under this note, such as for idlers and location of scale, will generally not apply to systems using a nuclear scale. The manufacturer should be consulted if applicability is unclear.

③ If a nuclear scale is used, the only contact requirement is for the belt speed indicator, which has a negligible impact on belt tension requirements.

④ "Car" refers to railroad car - for other coal sources, read as "The system must be so designed that all calibration material may be guaranteed to pass over the scale."

⑤ Incline is to prevent badslide of material and applies to nuclear scale instruments as well as mechanical and electromechanical ones.

⑥ Nuclear scale manufacturers' specifications indicate that the accuracy level may not be achievable for that device. If manufacturer's specifications are considered acceptable for a given application, then the scale is acceptable upon verification that it meets those specifications (in the absence, of course, of more stringent requirements from a regulatory body such as the Bureau).

⑦ The requirement for 10 to 15 car loads corresponds to ∿2000 tons of coal, and is usually used in calibration of conveyors with approximately 8000 tons per hour capacity, which corresponds to a nominal calibration run time of 15 minutes. This quantity of coal would be inappropriate for very small capacity units. As a rule of thumb, it may be considered acceptable to use a quantity of coal which would result in a run time of at least 15 minutes at 80% capacity and at least three complete circuits of the belt.

⑧ The nuclear scales, a (static) plate takes the place of test chains. The belt should be running, empty, when the plate is being used to account for effects of the belt itself.

⑨ Some manufacturers offer a static test weight for calibration purposes. This can be used to accurately check the load cell itself, but will not indicate systematic errors due to changes in belt tension and other factors related to the conveyor belt/weighbridge interface in mechanical and electromechanical systems.

⑩ Belt length concerns show a need for good communication between user and vendor so that appropriate hardware is purchased. Very short (1-3 m) conveyors are usually purchased as a packaged system, often including the hopper which feeds the belt.

⑪ "One increment of the scale" requirement is listed as .01% in the first report.

Afterthought: Nowhere in manufacturers' data which we have examined is there an indication of need for the care and attention to detail indicated in these reports. Many of the small details are not expensive or time-consuming, and several need to be performed only once. Simple operation descriptions by sometimes overzealous marketing people should not lead users to the conclusion that installation and operation details as described in these reports may be glossed over or dismissed.

REVIEW COMMENTS

In his review of the draft report, Mr. Martin Gruber of the Southern Weighing and Inspection Bureau returned the following comments (presented verbatim):

1. - Page 121. No. 10, Footnote 1. Of primary importance to anyone who depends on results from belt conveyor scales is an accurate weight. A rate-of-flow chart allows complete supervision of the instrument without the necessity of having an employee making constant observation.

2. - Page 122. No. 23, Footnote 1. It has been our experience that the mere act of barring access to a belt scale adjustment mechanism by the simple process of locking cabinet doors has resulted in more accurate scales and less frequent overhauls. Locking access doors allows the key holders to have complete control over unauthorized tampering.